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(73) Proprietor : **THE BOARD OF TRUSTEES OF**  
**THE LELAND STANFORD JUNIOR**  
**UNIVERSITY**  
**350 Cambridge Avenue,**  
**Suite 250**  
**Palo Alto, California 94306 (US)**

(72) Inventor : **ALBRECHT, Thomas, R.**  
**5355 Wong Court**  
**No. 231**  
**San Jose, CA 95123 (US)**  
Inventor : **ZDEBLICK, Mark, J.**  
**27741 Via Cerro Gordo**  
**Los Altos Hills, CA 94022 (US)**

(74) Representative : **Cross, Rupert Edward Blount**  
**et al**  
**BOULT, WADE & TENNANT**  
**27 Fumival Street**  
**London EC4A 1PQ (GB)**

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## Description

The invention pertains to the field of scanning tunneling microscopes, and more particularly, to the field of integrated versions of same.

5 Scanning tunneling microscopes were first invented by a team of researchers from IBM (Binnig and Rohrer). The basic concept of a scanning tunneling microscope is to place a very sharp, conducting tip having tip dimensions on the order of the size of 1 atom in diameter close to a conductive surface. If the tip is brought very close to a conductive surface, i.e., within the space of the diameters of several atoms, (approximately within 5 angstroms), a tunneling current flows between the tip and the surface. That is, the probability density  
10 function of electrons for atoms in the tip overlaps in space the probability density function of electrons for atoms on the surface. As a result, tunneling occurs in the form of electron current flow between the tip and the surface if a suitable bias voltage between these two conductors is applied.

The magnitude of the tunneling current is exponentially dependent upon the distance between the tip and the surface. If the distance between the tip and the surface increases by only 1 angstrom, the current is reduced  
15 by a factor of 10. Typically, 100 millivolts of bias voltage will provide 1 nanoampere of current for a tip to sample spacing of a few angstroms.

This tunneling current phenomenon can be used to take an image of the surface. To do this, the tip must be placed very close to the surface and must be moved in raster scan-like fashion across the surface while maintaining the relative distance between the tip and the surface. The tip must be moved up and down to follow  
20 the contour of the surface to maintain a relatively constant distance between the highest point on the surface and the tip. This distance must be accurately maintained to be within the tunneling overlap distance to maintain constant current flow. As the tip is scanned across the contour of the surface, an image of the surface contour may be built up by keeping track of the movements of the tip. Typically this process of tracking the tip movement is done by keeping track of the voltage applied across a piezoelectric transducer which moves the tip to main-  
25 tain the constant distance between the tip and the surface. Typically the apparatus that controls the tip distance monitors the current flowing between the tip and the surface and controls a mechanical system to move the tip in such a manner as to stabilize the current flowing between the tip and the surface at some steady state value. Thus, changes in the current will result in changes in the distance between the tip and the surface so as to counteract the changes in the current and stabilize it at a steady state value. Thus, changes in the drive  
30 signals to the tip movement mechanism track changes in the surface contour as the height of the tip above the surface is adjusted to maintain constant current.

A collection of papers defining the state of the art in scanning tunneling microscopy is published in the IBM Journal of Research and Development, Vol. 30, No. 4, pages 353-440, July 1986. In an article entitled  
35 "Scanning Tunneling Microscopy" by Binnig and Rohrer at pages 355-369 of that journal, a scanning tunneling microscope is depicted in Figure 2 using a piezoelectric tripod. This tripod consists of 3 piezoelectric rods of material joined at a junction; each rod expands and contracts along one of 3 Cartesian coordinate axes. The tip is mounted at the junction of the 3 rods. The tip is brought into proximity of the surface by a rough positioner. Thereafter the piezoelectric tripods are used to scan the tip across the surface to develop an image of that surface. The collection of papers in the IBM Journal of Research and Development shows scanning tunneling  
40 microscopy as being done with large scale apparatus.

One reference teaches an integrated form of a scanning tunneling microscope. This reference is European Patent Application Publication No. 0194323A1 published 17 September 1986 based on European Application 85102554.4 filed 3 July 1985. This patent application describes a scanning tunneling microscope integrated  
45 on a semiconductor chip into which slots are etched to form a center portion cantilever. The slots are etched to have mutually orthogonal directions to allow the center portion to perform movements in the X and Y direction under the control of electrostatic forces created between the stripes defined by the slots and their opposite walls. A protruding tip is formed on the center portion which is capable of being moved in the Z direction by means of electrostatic forces. Electrostatic forces are not ideal for tip movement to obtain maximum accuracy. Also, the integrated STM described in the European Patent Application cited above would be difficult to suc-  
50 cessfully fabricate.

Thus, a need has arisen for an integrated version of the scanning tunneling microscope using piezoelectric means for moving the tip.

The present invention provides an integrated scanning tunneling microscope comprising a motion transducer integrated on a substrate and having a protruding conductive tip, terminating in a point; means coupled  
55 to said motion transducer for holding a conductive surface at a fixed position close to said conductive tip such that movement of said motion transducer is sufficient to bring said conductive tip within tunneling range of said conductive surface; bias means for applying a bias potential between said tip and said conductive surface sufficient to cause tunneling current to flow between said tip and said conductive surface; sensing means for sens-

ing the magnitude of the tunneling current flow; and control means coupled to said bias means and said motion transducer to position said tip so as to adjust said tunneling current; characterized by said motion transducer comprising a three-axis movement piezoelectric bimorph cantilever attached to said substrate at one end with said tip positioned at a second end of said cantilever, said bimorph cantilever including a first plurality of electrodes, a second plurality of electrodes, two layers of piezoelectric material sandwiched between said first and second plurality of electrodes, and an electrode sandwiched between said two layers of piezoelectric material; wherein said bimorph cantilever moves in response to potentials applied to said electrodes; and said control means including means for apply voltage potentials to said electrodes of said bimorph cantilever so as to move said tip.

The present invention also provides a method of forming an integrated scanning tunneling microscope comprising fabricating a motion transducer integrally with a substrate; growing on said motion transducer a protruding conductive tip, terminating in a point; positioning a conductive surface at a fixed position close to said conductive tip such that movement of said motion transducer is sufficient to bring said conductive tip within tunneling range of said conductive surface; providing bias means for applying a bias potential between said tip and said conductive surface sufficient to cause tunneling current to flow between said tip and said conductive surface; and providing sensing means for sensing the magnitude of the tunneling current flow; characterized by said motion transducer fabricating step fabricating a piezoelectric bimorph cantilever integrally with said substrate at one end with said tip positioned at a second end of said cantilever, including the steps of depositing a first conductive layer on said substrate and patterning said first conductive layer into a first plurality of electrodes; depositing a first layer of piezoelectric material over said first conductive layer; depositing a second conductive layer over said first layer of piezoelectric material; depositing a second layer of piezoelectric material over said second conductive layer; depositing a third conductive layer over said second layer of piezoelectric material and patterning said third conductive layer into a second plurality of electrodes; removing a portion of said substrate from below said first conductive layer such that said bimorph cantilever has said one end attached to said substrate and said second end in free space; and providing control means, coupled to said bias means, sensing means and said electrodes, for adjusting the potentials applied to said electrodes so as to move said tip.

According to the teachings of the invention, there is disclosed an integrated scanning tunneling microscope using a piezoelectric bimorph cantilever for the necessary tip movement.

In one embodiment, a layer of spacer material which will later be removed, is placed over the surface of a silicon or other substrate. Thereafter, a layer of conductive material is formed on the spacer layer and patterned to form three separate electrodes. Then a layer of piezoelectric material is formed over the three electrodes and another layer of conductive material is formed over the layer of piezoelectric material. A second layer of piezoelectric material is then formed over the middle conductor. Finally, a third conductive layer is formed over the second piezoelectric material layer and is patterned to form three separate electrodes which are aligned with the three separate electrodes of the bottom-most conductive layer. Then a sharp, conductive tip is formed on the center electrode on the uppermost conductive layer. This tip is formed by evaporation deposition of a conductive material through a shadow mask. The evaporation deposition forms a cone of material of ever decreasing diameter on the center, top electrode. The ever-decreasing diameter results as the material landing on the shadow mask slowly closes off the hole in the mask above the point where the tip is being formed.

After the foregoing structure is formed, the sides of the piezoelectric material are etched away to form the bimorph lever. This etching is performed in such a manner that sufficient piezoelectric material is left on the sides to completely encase the center electrode. This etching of the piezoelectric material is done by first depositing a layer of titanium/tungsten metal and patterning this layer to act as an etch mask. This layer of metal is patterned using conventional photolithography techniques to define where the edge of the piezoelectric material is to be. After the metal etch mask is formed, the zinc oxide piezoelectric material is etched using the metal mask as a guide. If other piezoelectric materials are used which may be etched with good resolution, this step of depositing and forming a metal etch mask may be eliminated. Zinc oxide is a piezoelectric material which cannot easily be etched with good resolution. The step of forming the metal etch mask substantially improves the resolution which may be obtained in etching the zinc oxide material. "Resolution" as the term is used here is intended to specify the degree of control over the position of the edge of the zinc oxide.

After the piezoelectric material has been etched, the spacer material underlying the entire structure is removed. This spacer material is removed only up to the point where the cantilever bimorph is to be physically attached to the substrate. Removal of the spacer material causes the bimorph cantilever to extend out from its attachment point over the substrate with an air space between the bottom of the bimorph and the top surface of the substrate. This allows the bimorph to move up and down normal to the surface of the substrate by the effect of the piezoelectric material thereby allowing the tip to be moved. The existence of four pairs of electrodes and two layers of piezo material in this embodiment, allows three axis movement of the tip to be obtained.

To operate the structure just described so as to cause the tip to make raster scanning movements, various voltage combinations are applied to the four pairs of electrodes formed by the middle layer electrode and the outer electrodes on the bottom and top electrode layers. By suitably controlling the voltages applied to these four electrode pairs, the tip may be made to move along any of the three axes in a Cartesian coordinate system.

5 In alternative embodiments, a cantilever structure having two arms each having two piezo layers but only two pairs of electrodes, formed as previously described, may be fabricated so as to extend out over the substrate from their attachment points and to intersect each other at a 90° angle and to be joined at the intersection. These two arms may then be controlled in a similar manner to the manner described above for a single arm structure to move the intersection point along any of the three axes of a Cartesian coordinate system. In an alternative embodiment, two conductive tips may be formed at the end of the bimorph and the voltages applied to the electrodes may be manipulated so that the tip of the bimorph rotates to provide independent Z axis motion for each tip and synchronous X and Y motion for both tips.

10 An alternative, and preferred, embodiment of the method for forming the bimorph piezoelectric transducer structure described above, is to form the multilayer structure directly on a silicon substrate without any spacer material as described above but to free the bimorph cantilever from the substrate by etching through to the under surface of the cantilevered bimorph from the back side of the wafer.

A scanning tunneling microscope according to the teachings of the invention may be made by using any of the processes described herein to manufacture a bimorph tip movement structure and then placing the tip sufficiently close to a conductive surface to be scanned such as by attaching to the substrate on which the bimorph is integrated another wafer containing the conductive surface to be scanned. Suitable known control circuitry may then be integrated on either substrate if it is of semiconductor material to sense the tunneling current and to control the voltages applied to the electrodes of the bimorph.

20 The scanning tunneling microscope structures in integrated form described herein have many potential applications including imaging at the atomic level, atomic scale lithography and mass storage. Mass storage systems of very high density can be formed using such a structure by defining a discrete number of "cells" within the raster scannable surface of a conductive plane formed adjacent to the tip. Each cell constitutes one memory location. Each memory location is written as a 1 or 0 by depositing a molecule of sufficient size to be detected by the scanning tunneling microscope within each cell to form a 1 and not depositing such a molecule in the cell to form a 0. As the scanning tunneling microscope raster scans over such a surface, those cells wherein molecules are deposited are read as ones as the tip is forced by its control system to move away from the surface to maintain a steady tunneling current as the tip passes over the molecule. Essentially, the molecule forms a "hill" in an otherwise smooth surface. This hill causes the distance between the tip and the top of the molecule to decrease, thereby substantially increasing the tunneling current. The control system detects this increase and sends the appropriate voltages to the bimorph cantilever to cause the tip to move away from the surface sufficiently to bring the tunneling current back down to the constant level for which the system is calibrated. This movement of the tip or change in the voltages sent to the bimorph electrodes is detected and read as a logic 1. Other circuitry keeps track of the tip position and signals as each new cell is traversed. Thus, such a movement of a tip as it traverses a particular cell can be read as a 1 and lack of movement as it traverses another cell can be read as a 0. Such mass storage systems have the potential for tremendous information storage density because of the small, atomic scale dimensions involved.

30 Imaging applications of such a scanning tunneling microscope provide the ability to see the characteristics of surfaces on an atomic scale with greater resolution than has heretofore been attained. This allows the examination of such surfaces as semiconductor substrates during various stages of processing for research and development or quality control purposes. Vast numbers of other applications will be appreciated by those skilled in the art.

45 Figure 1 is diagram of typical scanning tunneling microscope system.

Figure 2(a) and 2(b) are a view of a prior art discrete, large scale scanning tunneling microscope invented by IBM.

50 Figures 3-10 are successive cross sectional views along the transverse axis of the bimorph cantilever of the intermediate stages in a first process of fabrication of the preferred structure for an integrated single arm bimorph cantilever with tip for a scanning tunneling microscope according to embodiments of the invention.

Figure 11 is a cross sectional view of the final scanning tunneling microscope preferred structure taken along the longitudinal axis of the bimorph cantilever.

55 Figure 12 is a plan view of the one arm cantilever bimorph structure according to a preferred embodiment of the invention.

Figure 13 is a diagram of the four pairs of electrodes 1 in the one arm cantilever bimorph used to explain how three axis motion is achieved.

Figure 14 is a table of the various voltages that be applied to achieve motion in any particular axis.

Figures 15-20 are cross sectional diagrams longitudinally through one arm of an alternative two arm bimorph piezoelectric cantilever according to one embodiment of the invention.

Figure 21 is a transverse cross section of the bimorph construction in two arm bimorph embodiments.

Figure 22 is a plan view of a two arm bimorph embodiment of the invention with no control circuitry integrated on the substrate.

Figures 23-33 are cross sectional views of intermediate stages in the preferred process for construction of an integrated piezoelectric transducer and scanning tunneling microscope having either the preferred structure shown in Figure 10 or the two arm structure shown in Figures 20 and 22.

Figures 34(a) and (b) through 36(a) and (b) represent the types of X, Y and Z axis motion that can be achieved with single tip bimorphs having the structure shown in cross section in Figure 10.

Figures 37(a) and (b) represent the types of rotational motion that can be achieved in two tip embodiments using a bimorph having the construction shown in Figure 10 to provide independent Z axis motion and synchronous X and Y motion.

Before discussing the details of the preferred and alternative embodiments of the integrated piezoelectric transducer, a scanning tunneling microscope (STM) using this transducer and methods for making these structures, it would be helpful to understand the teachings of the invention to explore the current state of the prior art in STM's. Figure 1 depicts a prior art scanning tunneling microscope system which can be integrated according to the teachings of the invention. In Figure 1, a conductive surface 10 having topographical features 12 and 14, etc., is scanned by a conductive tip 16. This tip is very narrow at its point, and preferably terminates in a single atom at the point 18.

The point 18 is scanned over the conductive surface 10 by a piezoelectric transducer 20. The purpose of this piezoelectric transducer is to scan the tip over the surface by defining a plurality of raster scan lines in the X-Y plane. The transducer 20 also moves the tip back and forth along the Z axis as the tip is scanned in the X-Y plane so as to maintain a distance between the point 18 and the uppermost portion of the topographical feature over which the tip currently resides at a more or less constant distance. This distance is usually around 1 to 10 angstroms, and must be within the overlap region of the probability density functions of the electrons for the atoms in the point 18 and the atoms in the uppermost regions of the topographical feature over which the tip currently resides. As long as the distance between the tip and the surface is within the overlap region of the probability density functions (tunneling range - usually less than 10 angstroms) and a bias voltage is applied across this junction, a tunneling current will flow between the tip 18 and the conductive surface. This tunneling current is symbolized by the arrow  $I_T$ .

The magnitude of the tunneling current  $I_T$  is exponentially related to the distance between the tip and the surface. The magnitude of the tunneling current will decrease when the distance becomes larger and increase when the distance becomes smaller. To cause this tunneling current to flow, a bias voltage is applied between the tip 16 and the conductive surface 10 by a bias voltage source 22. A current sensor 24 senses the magnitude of the tunneling current  $I_T$  and outputs a feedback signal on line 26 which is proportional to the magnitude of the tunneling current. A feedback circuit in control system 28 receives this feedback signal and generates suitable piezotransducer driving signals on the bus 30 to cause the piezoelectric transducer to move the tip 16 in such a manner as to maintain the tunneling current  $I_T$  at a relatively constant value. The control system 28 also generates suitable piezoelectric transducer driving signals on the bus 30 to cause the tip 16 to be raster scanned across the conductive surface.

Figure 2 is a diagram of a typical scanning tunneling microscope prior art structure as developed by IBM and as discussed in the above cited IBM Journal of Research and Development. Figure 2 shows the mechanical details of the structure. The microscope tip T is scanned over the surface of a sample S with a piezoelectric tripod (X, Y, Z) in Figure 2(a). A rough positioner L brings the sample within reach of the tripod. A vibration filter system P protects the instrument from external vibrations. In the constant tunneling current mode of operation, the voltage  $V_Z$  is applied to the Z piezoelectric element by means of the control unit CU depicted in Figure 2(b). The control unit keeps the tunneling current constant while the tip is scanned across the surface by altering the control voltages  $V_X$  and  $V_Y$ . The trace of the tip generally resembles the surface topography. Inhomogeneities in the electronic structure of the sample's surface also produce structure in the tip trace. This is illustrated on the right half of the sample S as two surface atoms which have excess negative charge.

#### Process #1

Referring to Figure 3 there is shown an integrated structure representing an intermediate stage after the first several steps in a process for making an integrated scanning tunneling microscope using an integrated piezoelectric transducer. Fabrication starts with a substrate 32. Preferably this substrate is silicon or some other substrate suitable for forming integrated electronic circuits. However, the substrate may be any other

material which is chemically, mechanically and thermally compatible with the materials which will be formed on top of the substrate. It is preferable to make the substrate 32 of a semiconductor material so that the control circuitry which will be used to cause the tip movement via the piezoelectric bimorph can be formed on the same substrate as the bimorph itself.

5 The first step in the fabrication sequence is to deposit a spacer layer 34 under the portion of the bimorph that is to be cantilevered. The bimorph will be attached to the substrate at the end opposite the tip, so no spacer material is formed in this attachment region. This spacer layer will later be removed to provide a space between the uppermost surface (most positive Z coordinate) of the substrate 32 and the undersurface (most negative Z coordinate) of the piezoelectric bimorph which will be formed on top of the spacer layer 34. This will provide  
10 a clearance space for the piezoelectric bimorph to move along the Z axis. Preferably the spacer material is titanium, titanium tungsten or polyimide. This spacer layer must be of a material such that it can be selectively etched without having the etchant attack the material of the substrate 32 or the material of the overlying electrode and piezoelectric material layers. This class of materials will be hereafter referred to as the class 1 group of materials. Any material which can be selectively etched without attacking the materials of the other layers  
15 will suffice for purposes of practicing the invention. Titanium/tungsten alloy (10% Ti: 90% W) is a class 1 material selectively etchable by hydrogen peroxide if the conductors are aluminum and the piezoelectric material is zinc oxide. Polyimide is another example of a class 1 material which can be selectively etched with an oxygen plasma. The thickness of the spacer layer 34 should be adequate to provide sufficient space for the bimorph to move in the negative Z direction.

20 Next, a layer of conductive material is deposited on top of the spacer layer. This layer of conductive material is photolithographically patterned and etched to form three electrodes 36, 38 and 40. The purpose of these electrodes will become clear later when the operation of the entire structure is detailed. Note, that although electrode 38 is shown to be more narrow than the electrodes 36 and 40 in the figures, in reality the electrodes 36, 38 and 40 are usually all the same size. This does not have to be the case however. The conductive layer  
25 from which the electrodes 36, 38 and 40 are formed is preferably of aluminum and is deposited to 0.1 to 1.0  $\mu$ m thickness. The electrodes 36 and 40 are patterned to be approximately 3 to 100  $\mu$ m wide each.

Referring to Figure 4, there is shown another intermediate stage in the fabrication of the integrated piezoelectric scanning tunneling microscope after the first layer of piezoelectric material has been deposited. After formation of the first three electrodes, the next step in the process is to deposit the first layer of piezoelectric material over the entire surface of the chip. This layer 42 is zinc oxide in the preferred embodiment of the structure and is deposited to 2  $\mu$ m thickness by reactive sputtering in an oxygen ambient. Methods for depositing zinc oxide are well known and are described in the following references which are hereby incorporated by reference: Rozgonyi and Polito, Preparation of ZnO Thin Films By Sputtering of the Compound in Oxygen and Argon, Applied Physics Letters, pp. 220-223, Vol. 8, Number 9 (1966); Denburg, Wide-Bandwidth High-Coupling Sputtered ZnO Transducers on Sapphire, IEEE Transactions On Sonics and Ultrasonics, pp.31-35, Vol. SU-18, No. 1, (Jan. 1971); Larson et al., RF Diode Sputtered ZnO Transducers, IEEE Transactions on Sonics and Ultrasonics, pp. 18-22 (Jan. 1972); Shiosaki et al., Low-Frequency Piezoelectric-Transducer Applications of ZnO Film, Applied Physics Lett., pp. 10-11, Vol.35, No. 1, (1 July 1974); Khuri-Yakub et al., Studies of the Optimum Conditions For Growth of RF-Sputtered ZnO Films, pp. 3266-3272, Journal of Applied Physics, Vol. 46, No. 8 (Aug. 1975); Chen et al., Thin Film ZnO-MOS Transducer With Virtually DC Response, pp. 945-948, 1985 Ultrasonics Symposium of IEEE; Royer et al., ZnO on Si Integrated Acoustic Sensor, pp. 357-362, Sensors and Actuators, 4 (1983); Kim et al., IC-Processed Piezoelectric Microphone, pp. 467-8, IEEE Electron Device Letters, Vol. EDL-8, No. 10 (October 1987). Next, a layer of conductive material 44 is deposited over the first piezoelectric layer 42. The purpose of this conductive layer is to form a center electrode between the  
45 two layers of piezoelectric material which will be used to form the bimorph. Preferably, the layer 44 is aluminum and is deposited to 0.1 to 1.0  $\mu$ m thickness. From this layer a center electrode is photolithographically formed to be approximately 10 to 200  $\mu$ m wide.

Referring to Figure 5, there is shown another intermediate stage in the fabrication of the bimorph after the second piezoelectric layer has been deposited. This second piezoelectric layer 46 is zinc oxide in the preferred embodiment of the structure and is deposited to 2  $\mu$ m thickness. Next a layer of conductive material is deposited on top of the second piezoelectric layer 46. Preferably, this layer of conductive material is approximately 0.1 to 1.0  $\mu$ m thick aluminum. In some embodiments, an additional 1000 angstroms of gold is deposited on top of the aluminum. From this conductive layer, three electrodes 48, 50 and 52 are formed by photolithographic patterning. These electrodes are aligned with the locations of the electrodes 36, 38 and 40 and have the same  
55 widths as those electrodes. Preferably, the electrodes 48, 50 and 52 are deposited using lift-off techniques.

Referring to Figure 6, there is shown an intermediate stage in the process of manufacture after the first few steps of the process of forming the tip on the center electrode 50 have been performed. Fabrication of metal cones by evaporation is not a new technique, but has been previously described by Spindt et al., J. Appl.

Phys., 47, 5248 (1976). Figure 6 depicts an alternative embodiment of the tip formation process using an integrated shadow mask.

Basically the process of forming a tip having sufficient sharpness is best done through the use of a shadow mask. In Figure 6, this shadow mask is formed from layers which are deposited over the uppermost group of three electrodes 48, 50 and 52. In the preferred embodiment of the structure, a separate wafer is processed to form a shadow mask with alignment keys, and this separate wafer is placed over the structure shown in Figure 5 by aligning the alignment keys on each wafer. The separate wafer and the structure of Figure 5 are then processed to have lock and key physical characteristics such that the aperture in the shadow mask can be properly aligned over the center electrode 50. In the alternative embodiment shown in Figure 6, the first step in forming the integrated shadow mask is to deposit a layer 54 of the class 1 spacer material. Again, this layer 54 must be selectively etchable by an etchant which will not attack the material of the electrodes 48, 50 and 52, or the zinc oxide of the layers 46 and 42. The layer of the spacer material 54 need not be the same type of material as used in the spacer layer 34. However, the material of both of these layers must be within the class 1 group of materials. No patterning is performed on the layer 54, and it is allowed to cover the entire structure. Next, a layer 56 of a class 2 material, preferably copper, is deposited over the spacer layer 54. A class 2 material is any material which may be selectively etched by an etchant which will not attack the class 1 material used above and below it and which can be etched away after tip formation without etching the material of the tip. In the preferred embodiment of the structure, the spacer layer 54 is 1000 angstroms of titanium/tungsten alloy. The layer 56 of class 2 material is preferably 2  $\mu$  of copper. Next, a 5000 angstrom layer 58 of class 1 spacer material is deposited over the class 2 layer 56.

Figure 7 shows the integrated structure at an intermediate stage during formation of the tip after etching of the spacer layer 58 and underetching of the class 2 layer 56. The formation of the tip is done by evaporation of a metal through a shadow mask aperture. This shadow mask aperture must be raised above the surface upon which the tip is to be formed so that a cone of material may be built up before the shadow mask aperture is closed off by the deposition of the material on top of the shadow mask. In Figure 7, the shadow mask is the layer 58 and the shadow mask aperture is the opening 60 in this layer. The opening 60 is formed by using a selective etchant for the class 1 material of layer 58 and conventional photolithographic techniques. The aperture 60 is defined to be 1-2  $\mu$  and is centered over the center of the electrode 50. Generally, the size of the aperture 60 should be much smaller than the size of the middle electrode 50. If the class 1 material of layer 58 is titanium/tungsten alloy, a suitable etchant for this selective etching step would be hydrogen peroxide.

After the aperture 60 is etched, the copper layer 56 must be etched back so as to underetch the perimeter of the aperture 60. The purpose for this underetching step is to provide clearance space for the walls of the tip cone which is to be formed later. The underetching step of the class 2 material of layer 56 is performed using a selective etchant which only attacks the class 2 material. If layer 56 is copper, this etch is performed using the aperture 60 as a mask and using a mixture of nitric acid, hydrogen peroxide, and water in a ratio of 10:1:100, respectively. That is, the etchant is 10 parts  $\text{HNO}_3$  to 1 part  $\text{H}_2\text{O}_2$  to 100 parts  $\text{H}_2\text{O}$ .

Referring to Figure 8, there is shown the state of the structure in the intermediate stage of construction after formation of the tip but before removal of those layers which were formed in the process of forming the tip. Prior to the evaporation deposition of the tip material, a third etch step is performed to selectively etch through the class 1 material of layer 54 to form an aperture over the center electrode 50. In some embodiments, a cleaning step will then be performed to clean the surface of the electrode 50 to prepare it for tip deposition. This is done to better insure adhesion of the tip material to the electrode 50. The selective etching of the layer 54 is performed using a timed liquid etch or plasma etch to expose the top surface of the electrode 50. This etching step also etches a little of the layer 58 and all of layer 54 down to the electrode 50. For this reason, the layer 58 should be formed at least twice as thick and preferably 3 times as thick as the layer 54. A timed sputter etch is used to clean the surface of electrode 50 if needed. Where the boundary of the aperture in the layer 54 is relative to the boundary of the aperture in the layer 56 depends upon whether a liquid or plasma etch is used to etch the layer 54. The boundary of the aperture in the layer 54 will be colocated with the boundary of the aperture in the layer 56 for liquid etches and will be approximately located with the boundary of the aperture 60 in the layer 58 if a plasma etch is used.

Next, the tip 66 is formed. In the preferred embodiment of the structure, this tip is formed by evaporation in vacuum of tantalum or some other class 3 material. Any other material can be used for the tip 66 if it has the characteristics of a third class of materials hereafter defined. A class 3 material must be such that it does not oxidize appreciably in air and it must be such that it will not be etched by the etchant used to selectively etch the class 2 material of layer 56. Tantalum is such a material if copper is selected for the layer 56. Other possible materials for the tip would be aluminum coated with a noble metal by evaporation. Alternatively, the tip can be a noble metal standing alone, or any other conductor that can be selectively etched in the manner described above.

The evaporation of the class 3 material 62 from a point (approximately 1-5mm) located far (approximately 10 cm) above the surface results in the formation of the layer 64. Note that as the evaporation continues through the aperture 60, the aperture in the layer 64 slowly decreases in diameter as evaporation continues due to condensation of the evaporated material on the sidewalls of the aperture. As the diameter of the aperture in the layer 64 continually decreases, so does the diameter of the cone of material in the tip 66 being formed beneath this aperture. When the aperture in the layer 64 finally closes itself off, formation of the tip 66 is complete, and a very sharp tip (tip radius less than 1000 angstroms) will have been fabricated.

Referring to Figure 9, there is shown a cross section of the structure at an intermediate stage in the construction after lift-off of the shadow mask layers and deposition of a zinc oxide etch mask layer. Following the processing steps described with reference to Figure 8, it is necessary to remove the layers 54, 56, 58 and 64 so as to expose the tip 66. This is done using a lift-off etch to remove the class 2 material of layer 56. This lift-off etch removes all the layers above layer 54, i.e., the class 2 layer 56, the class 3 layer 64 and the class 1 layer 58.

Next, it is necessary to etch the piezoelectric layers 47 and 42 to define the sidewalls of the bimorph cantilever beam. This is done by photolithographically patterning the remaining layer 54 to serve as an etch mask for the zinc oxide as described previously. Layer 54 is patterned to have the configuration shown in Figure 9. Note that the edges 70 and 72 of this layer are located along the X axis outside of the edges 74 and 76 of the metal electrode layer 44. The reason for this location is to insure that the edges 74 and 76 of the middle electrode are completely encased in the zinc oxide of the layers 46 and 42. The purpose for this is to prevent leakage currents and arcing between the electrodes 36, 40, 44, 48 and 52 which would lower the breakdown voltages and prevent the device from operating at high voltages. The purpose of formation of the etch mask 68 is to improve the resolution of the etching of the piezoelectric layers 42 and 46. Etching of piezoelectric material such as zinc oxide using photoresist provides very bad resolution as to the exact location of the edge of the piezoelectric material relative to the edge of the photoresist. It has been found that substantial improvements in the certainty of the location of this edge can be made by first forming an etch mask of the class 1 material such as titanium/tungsten alloy and then using this etch mask to guide the etching of the piezoelectric material. Thus, after the layer 68 is formed, a solution of 15 grams  $\text{NaNO}_3$ , 5 ml  $\text{HNO}_3$  and 600 ml  $\text{H}_2\text{O}$  is used to etch the piezoelectric layers 46 and 42 back to the approximate location of the edges 70 and 72.

After the tip is exposed, and the piezoelectric layers are etched, the spacer layer 34 is selectively etched away to free the cantilever.

Figure 10 shows in cross section the preferred final piezoelectric bimorph transducer structure in integrated form according to the teachings of the invention after selective etching of the spacer material layers 34 and the etch mask layer 54. Note the aperture 78 formed by the removal of the spacer layer 34. It is this void which allows the tip 66 to move along the Z axis under the influence of the forces generated by the piezoelectric material.

Figure 11 shows a cross sectional view of the bimorph cantilever taken in the Y-Z plane, whereas the cross section of Figure 10 is taken in the X-Z plane. A plan view of the bimorph cantilever is shown in Figure 12 looking down the Z axis at the X-Y plane. Figure 12 shows the locations of the sections taken in Figures 10 and 11 as the section lines 10-10' and 11-11', respectively. Note in Figure 11 the cantilevered nature of the bimorph structure, the bimorph being attached to the substrate 32 only in the area 80. The relative dimensions in Figure 12 may be not truly indicative of an actual design which would be commercially employed. Bonding pads 89, 91 and 93 are coupled by conductive paths to the two electrode pairs comprised of electrodes 48, 36 and 44. Bonding pads 97, 99 and 101 are coupled by conductive paths to the two electrode pairs comprised of electrodes 52, 40 and 44. Bonding pad 95 is coupled by conductive paths to both the electrodes 50 and 38 and the tip 66. In embodiments where the control circuitry is integrated on the substrate 32, the bonding pads shown in Figure 12 can be eliminated.

#### Necessary Additional Elements Needed For An STM

Referring again to Figure 11, there are several additional elements of a scanning tunneling microscope system which are necessary for converting the cantilever bimorph piezoelectric transducer shown in Figure 11 to a system having multiple commercial applications. An overlying wafer 82 having a conductive surface 84 is formed with a cavity 86 such that the wafer 82 may be physically attached to the substrate 32 with the conductive surface 84 overlying and within several microns of the end of the tip 66, such that the tip can be brought up to the surface 84 by bending of the bimorph. In the preferred embodiment of the scanning tunneling microscope (STM) structure, the wafer 82 may be Pyrex or silicon, but, in alternative embodiments, the wafer 82 may be any other material which is mechanically, thermally, and chemically compatible with the materials used in the rest of the structure. Preferably, the material of the wafer 82 should be such that a good bond may



be made between the wafer 82 and the substrate 32, and such that suitable convenient fabrication techniques are known which may be used to form the cavity 82 and to attach a conducting surface 84 to the wafer 82. In still other alternative embodiments, the wafer 82 may be itself a conductive material such that no separate conductive surface 84 needs to be attached. In such embodiments, the cavity 86 should be such that the portion of the wafer 82 of interest is scanned by the tip 66. Also, the electrodes 36, 38, 40, 44, 48, 50 and 52 will have conductive pathways formed through the piezoelectric layers and across the surface of the substrate 32 to bonding pads such that the appropriate voltages may be applied to these electrodes to cause the tip 66 to scan in the desired manner. If these conductive pathways pass between the surface of the substrate 32 and the mating surface of the wafer 82, the materials for these two structural elements must be selected such that the conductive pathways may be properly formed.

In some embodiments, the control circuitry to supply the bias current to the tip 66 and to control the voltages applied to the various electrodes will be integrated on the substrate 32. The block 88 represents the integration of such known circuitry on the substrate in known manner. The position of the block 88 is illustrative only since this circuitry may be integrated on the side of the substrate, in a recess in the substrate, or on the reverse side of the wafer opposite the side from which the bimorph cantilever is formed. It is preferred to integrate the circuitry at a location to minimize the complexity of routing the various signals and control voltages to the appropriate nodes of the circuit.

The structure shown in Figure 11 can be used for mass storage, microscopic photolithography, imaging and other commercial applications.

Referring to Figure 13, there is shown a schematic diagram of a cross section through the bimorph cantilever to illustrate how the various electrodes are operated to cause movement of the cantilever in the Cartesian coordinate system. The cross section of Figure 13 has the same orientation as the cross section 10-10' in Figure 12. The vectors marked 1, 2, 3 and 4 in Figure 13 represent the electric field vectors existing between the four pairs of electrodes. The electric field vector 1 represents the field between the electrode 52 and the center electrode 44. The electric field vector 2 represents the field between the center electrode 44 and the outer electrode 40. The electric field vector 3 represents the field between the electrode 48 and the center electrode 44, and the electric field vector 4 represents the field between the center electrode 44 and the outer electrode 36. In each case, the electric field is directly proportional to the potential difference applied to the pair of electrodes bounding the region of interest.

The nature of the piezoelectric zinc oxide is such that if a field is applied in the Z direction (which is along the crystallographic C-axis of the material) that causes the material to contract along that axis, and the material simultaneously expands along both the X and Y axes. Only expansions or contractions along the Y axis cause any bending of the bimorph. Hence, the following discussion refers to Y-axis motion only.

Referring to Figure 14, there is shown a table of the desired movements in the Cartesian coordinate system having the axes oriented as shown to the left of Figure 13, said table correlating these desired movements to relative expansions in the piezoelectric material in accordance with the relationships given on the right half of the table. The manner in which the table of Figure 14 is interpreted is as follows. If it is desired to cause movement of the bimorph of Figure 13 in only the negative X direction, it is necessary to charge the electrodes 52 and 44, and 44 and 40, respectively, such that the relative Y-axis expansion of the piezoelectric material in the layers 46 and 42 between these two pairs of electrodes is equal. Further, it is necessary to charge the electrodes 48 and 44, and 44 and 36 such that the Y-axis expansion of the piezoelectric material in the layers 46 and 42 between these two pairs of electrodes is also equal, but such that the Y-axis expansion between the electrode pairs 48 and 44, and 44 and 46, respectively, is less than the expansion between the electrodes 52 and 44, and 44 and 40, respectively. In other words, if one thinks of the vectors marked 1-4 in Figure 13 as the relative magnitude of the Y-axis expansion of the piezoelectric material in the layers 46 and 42 in the localized areas through which these vectors pass, then to obtain negative X movement of the bimorph, it is necessary that the expansions in areas 1 and 2 be equal and greater than the expansions in areas 3 and 4. This causes movement of the bimorph in the negative X direction in the same mechanical fashion as a bimetallic strip works where one layer of metal in the bimetallic strip expands less than the other layer of metal. This causes forces which tend to cause the strip to bend toward the strip which expands less. From Figure 14, it is seen that for positive X expansion the situation is exactly opposite as the situation previously described. That is, the expansions in the areas 3 and 4 are equal and exceed the expansions in the areas 1 and 2. Likewise, for negative Y movement, i.e., movement into the page of the tip 66, it is necessary to charge the electrodes 48, 52, 44, 36 and 40 such that the piezoelectric material in regions 1-4 all contract an equal amount. This contraction is signified as expansion less than zero. For positive Y movement, it is necessary to charge the same electrode such that regions 1-4 all expand by the same amount which is signified by an expansion greater than zero. For positive Z movement, it is necessary to charge the electrodes such that regions 2 and 4 expand equally and greater than the expansion in regions 1 and 3. Likewise, for negative Z movement, it is necessary

to charge the electrode such that regions 1 and 3 expand an equal amount and greater than the expansion in regions 2 and 4.

It is possible to obtain any desired movement in the Cartesian space defined by the 3 axes coordinate system to the left of Figure 13 by superimposing these relationships from any one axis upon the relationships for another axis. That is, if both negative X and positive Y movement is simultaneously required, the relationships from these two lines of the table of Figure 14 are superimposed such that all four regions are expanded equally by an amount A to obtain the desired Y component with an additional expansion of regions 1 and 2 by an amount B over the expansion of regions 3 and 4 to obtain the desired negative X component. Note that electrode 50 only serves as a signal connection to the tip 66. The bottom electrode 38 is charged with the same bias voltage applied to the top center electrode 50 and the tip to eliminate any spurious, parasitic movements caused by expansion or contraction in the piezoelectric layer 46 under the center electrode 50. Any such movement is cancelled by the movements in the layer 42 caused by the charge on the bottom center electrode 38.

## Process #2

Beginning at Figure 15, the fabrication of the two arm bimorph embodiment of a piezoelectric transducer according to the teachings of the invention is shown. Note that Figures 15 through 20 show a view of one arm lengthwise similar to the view shown in Figure 11 of the transducer built according to the previously described process.

Referring to Figure 15, there is shown an intermediate stage in the process of making an arm of a two arm bimorph using a backside etch technique. A substrate 92 is chosen which is preferably a semiconductor, but which may also be, in alternative embodiments, other materials capable of being micromachined. Semiconductor is desirable for the substrate so that control circuitry may be integrated on the same die as the bimorph itself. The first step in the process is to grow a 500 angstrom thick layer of silicon dioxide 94. Next, a 900 angstrom thick layer of nitride ( $\text{Si}_3\text{N}_4$ ) is grown, and conventional photolithography techniques are used to define and etch a hole through the oxide layer 94 and nitride layer 96 to expose the surface of the substrate 92 as shown at 98.

Referring to Figure 16, there is shown another intermediate stage in the construction of a two arm bimorph after etching of the cavity. After defining the location of the aperture in the silicon dioxide and nitride layers as shown in Figure 15, a KOH etch is used to etch a 350  $\mu\text{m}$  deep trench in the substrate 92, using the nitride layer as an etch mask. This trench is shown at 100. Thereafter, the nitride layer 96 is stripped to leave only the silicon dioxide layer 94. Alignment marks are then patterned into side A to allow alignment to the pattern on side B (see Figure 15).

Figure 17 shows another intermediate stage in the process after deposition of the first electrode layer. The next step is to deposit 0.1 to 1.0  $\mu\text{m}$  of aluminum and to pattern it to form the electrode shown at 102.

Figure 18 shows another intermediate stage after deposition of the first piezoelectric layer and formation of a center electrode. After forming the electrode 102, a layer 104 of piezoelectric material is deposited. This layer is 2  $\mu\text{m}$  of zinc oxide or some other piezoelectric material. Next, a 0.1 to 1.0  $\mu\text{m}$  layer of aluminum is deposited and patterned and etched to form the center electrode 106.

Referring to Figure 19, there is shown an intermediate stage in the construction of the two arm bimorph after the second layer of piezoelectric material and the top electrode has been formed. After forming the middle electrode 106, 2  $\mu\text{m}$  of piezoelectric material are deposited in a layer 108. This layer is zinc oxide or some other piezoelectric material. Next, 0.1 to 1.0  $\mu\text{m}$  of aluminum and 1000 angstroms of gold are deposited over the piezoelectric layer 108. This layer of conductive material is then patterned and formed using lift-off techniques into the top electrode 110 and a tip electrode 112.

Referring to Figure 20, there is shown another intermediate stage in the construction of the two arm bimorph after the tip has been formed and the structure has been underetched to free the bimorph. The process for forming the tip 114 is the same as described with reference to Figures 3-10. After the tip is formed, the zinc oxide is patterned and etched to form the edge 116. This process is done using the same class 1 etch mask material as was used in the process described with reference to Figures 3-10. Finally, a plasma etch is used to etch through the remaining substrate 92 to the silicon dioxide layer 94 to free the bimorph arm from attachment to the substrate 92 along the area 118.

Figure 21 shows a cross section through the arm of bimorph shown in Figure 20 along the section line 21-21' in Figure 20. As can be seen from Figure 21 only two pairs of electrodes exist in the arm of the bimorph shown in Figure 21. These two pairs of electrodes are the electrode 110 and the electrode 106, and the electrode 106 and electrode 102, respectively. Those skilled in the art will appreciate that this structure will allow the arm bend up and down along the Z axis and expand or contract longitudinally along the X axis.

In order to get 3 axis Cartesian coordinate movement, a second arm having the structure shown in Figures

20 and 21 must be formed and joined to the arm of Figures 20 and 21 at the location of the tip 114. A plan view of the structure of this bimorph arrangement is shown in Figure 22.

Referring to Figure 22, the section line 20-20' indicates the position of the section through the structure of Figure 22 as shown in Figure 20. In the structure shown in Figure 22, two bimorph arms, 116 and 118, extend from the substrate 92 at right angles joined at the approximate location of the tip 114. The arm 116 can move the tip 114 up and down along the Z axis and longitudinally along the X axis. The arm 116 can move the tip up and down along the Z axis and longitudinally along the Y axis. The arm 118 has its three electrodes 110, 106 and 102 coupled respectively to the bonding pads 120, 122 and 124. These connections are made via electrical conductors 126, 128 and 130, which are photolithographically formed simultaneously with the electrodes 110, 106 and 102 on the surface of the substrate 92. The tip 114 is coupled by an electrical conductor 132 to a bonding pad 134. The corresponding three electrodes of the arm 116 are coupled to bonding pads 136, 138 and 140. In alternative embodiments, the circuitry to drive bias voltages onto the six electrodes to cause movement of the tip and to bias the tip 114 with a correct voltage could be integrated on the substrate 92 thereby eliminating the need for the bonding pads shown at the bottom of Figure 22. In such an embodiment, bonding pads would be present for supply of power to the circuitry used to bias the tip and drive the electrodes.

### Process #3-Preferred

The process described below is preferred to make either the one arm piezoelectric transducer having the structure of Figure 10 or the two arm bipod piezoelectric transducer shown in plan view in Figure 22 and in cross section in Figure 20. Referring to Figure 23, there is shown an intermediate stage in the preferred process for manufacturing a scanning tunneling microscope. The first step in the process is to clean a [100] silicon wafer 140 of 380 micron thickness with a standard acid clean. The details of this cleaning process are given in Appendix A which is a detailed process schedule for the preferred process. Next, a layer 136 of silicon dioxide is thermally grown to a thickness of 5000 angstroms. Then, a layer 138 of silicon nitride is deposited to 1000 angstroms thickness over the silicon dioxide using low pressure chemical vapor deposition (LPCVD).

Referring to Figure 24, there is shown the next stage in process after etching the backside pit. To free the bimorph cantilever to be formed later in the process, a backside etch is used. The first step in this process is to etch a pit in the backside. Negative photoresist (not shown) is applied and patterned to define the location of the pit. An oxygen plasma etch is then used to remove any remaining scum from the opening in the photoresist where the pit is to be formed. The details of this plasma etch are given in Appendix A. Next, the nitride layer 138 is etched using an  $\text{SF}_6$  and F13B1 plasma etch at a ratio of 1:1. Then, the oxide layer 136 is etched using a 6:1 buffered oxide etch solution (BOE). Following these two etch steps, the remaining photoresist (not shown) is removed and the wafer is cleaned using the process detailed in the appendix. Then 340 microns of silicon from the substrate 140 are etched away using the nitride/oxide layers as an etch mask. This etch is performed using a 30% KOH etch at 80 degrees C. The wafer is then rinsed in a 10:1  $\text{H}_2\text{O}:\text{HCl}$  solution, followed by a rinse in deionized water. This leaves the pit 142.

The substrate 140 has a polished front surface 144. Alignment marks are etched in this surface to facilitate the alignment of the various patterning steps to one another. Figure 25 shows the wafer after this alignment mark 146 has been etched. The procedure for forming these alignment marks starts by patterning photoresist to define the positions of the alignment marks 146. Then an oxygen plasma etch is used to descum the openings and the nitride layer 138 and the oxide layer 136 are etched using the same procedure defined above in describing Figure 24. A deionized water rinse and nitrogen ambient dry cycle are performed followed by etching of 3 microns of silicon using a 1:1  $\text{SF}_6:\text{C}_2\text{ClF}_6$  plasma etch. The wafer is then cleaned in accordance with the procedure outlined in Appendix A, and the remaining photoresist is removed. The layer of nitride 138 is then stripped using concentrated  $\text{H}_3\text{PO}_4$  at 165 degrees C for 1 hour followed by a deionized water rinse and a nitrogen ambient drying cycle.

The next stage is shown in Figure 26. To deposit the bottom electrode 148, the pattern of the electrode is defined with a positive resist liftoff process. Then the metal of the electrode is deposited by electron-beam evaporation deposition of 1000 angstroms of aluminum at room temperature. The excess aluminum is lifted off by soaking the wafer in hot acetone. The wafer is then rinsed in fresh acetone, methanol and deionized water and dried in a nitrogen ambient.

Figure 27 defines the next stage in the process. After deposition of the lower electrode, it is necessary to deposit the piezoelectric layer. This is done by first sputter cleaning the surface for 30 seconds and electron beam evaporation deposition of 1000 angstroms of silicon dioxide 150 on the substrate while holding the substrate at a temperature of 200 degrees C. Next, a 2 micron layer 152 of zinc oxide is sputter deposited using a zinc target in 5:1  $\text{O}_2:\text{Ar}$  gas ambient at 30 mTorr. During this process, the substrate is held to 300 degrees C. Then, a 1000 angstrom layer 154 of silicon dioxide is deposited over the zinc oxide by E-beam evaporation

with the substrate at 200 degrees C.

Figure 28 shows the intermediate stage in the process after the middle electrode is formed. To deposit the middle electrode 156, the pattern for the electrode is defined using mask #4 and positive resist and a liftoff technique. Next, a 1000 angstrom layer of aluminum is deposited by electron beam evaporation using a room temperature wafer holder. The excess aluminum is then lifted off by soaking the wafer in hot acetone. The wafer is then rinsed in fresh acetone, methanol and deionized water followed by a drying cycle in nitrogen ambient.

Figure 29 shows the stage of the process after the upper oxide layers have been deposited. The first step in this process is to sputter clean the wafer for 30 seconds. Next, 1000 angstroms of silicon dioxide 158 are E-beam evaporation deposited with the substrate held at 200 degrees C. The top layer of piezoelectric material 160 is formed by depositing 2 microns of zinc oxide using a zinc target in a 5:1 mixture of oxygen and argon at 30 mTorr with the substrate at 300 degree C. Finally, a 1000 angstrom layer 162 of silicon dioxide is E-beam evaporation deposited over the zinc oxide with the substrate at 200 degrees C.

Figure 30 shows the state of the wafer after the top electrode is formed. The top electrode 164 is formed by defining the pattern using a positive resist liftoff process. Then 500 angstroms of aluminum are deposited using a room temperature wafer holder and E-beam evaporation. This deposition is followed by an E-beam evaporation deposition of 500 angstroms of gold using a room temperature wafer holder. The excess gold and aluminum are then lifted off by soaking the wafer in hot acetone. The wafer is then rinsed in fresh acetone, methanol and deionized water and dried in a nitrogen ambient.

Figure 31 shows the wafer after the oxides have been patterned. The first step in this process is to sputter deposit 3000 angstroms of titanium/tungsten using an unheated wafer holder. Then the pattern for the oxide is defined in the titanium/tungsten layer which is to be used as an etch mask. This is done by defining the desired pattern in photoresist deposited on the titanium/tungsten and etching the titanium/tungsten layer using 30%  $H_2O_2$  for 30 minutes at room temperature. The wafer is then rinsed in deionized water and dried in a nitrogen ambient. Patterning of the oxides then begins with etching of the top silicon dioxide layer 162 using 6:1 buffered oxide etch, followed by a deionized water rinse. The upper zinc oxide layer 160 is then etched in a solution comprised of: 15 grams of  $NaNO_3$ , 5 ml  $HNO_3$ , 600 ml  $H_2O$  followed by a deionized water rinse. The middle layer 158 of silicon dioxide is then etched in the same manner as the layer 162, and the bottom layer 152 of zinc oxide is then etched using the same solution makeup as was used to etch the top layer 160. The bottom layer of silicon dioxide 150 is then etched using the same solution makeup used to etch the other layers of silicon dioxide. The wafer is then rinsed in deionized water and dried. Next, 3 microns of silicon are removed from the top of the wafer in regions where all upper layers have been removed to expose the silicon substrate. This is done using a 1:1  $SF_6:C_2ClF_5$  plasma etch. The wafer is then cleaned and the resist is stripped using acetone, methanol and deionized water. The remaining titanium/tungsten etch mask is then removed in 30%  $H_2O_2$  for 30 minutes at room temperature. The wafer is then rinsed in deionized water and dried.

After the oxide layers are etched, the bonding pad metal is deposited by defining the pattern by a positive photoresist liftoff process. The metal is then deposited using E-beam evaporation of 1 micron of aluminum using a room temperature wafer holder. The excess aluminum is then lifted off by soaking the wafer in hot acetone. The wafer is then rinsed in fresh acetone, methanol and deionized water and dried.

Next, the wafer side B is scribed using a diamond-tipped saw.

Figure 32 shows the wafer after the shadow mask for tip formation has been put into place and the tip deposition has taken place. First, the wafer is sputter cleaned for 30 seconds. Then, a separate wafer is fabricated to have the cross section shown in Figure 32. This wafer has an aperture 166 formed therein and has alignment marks that match the alignment marks 146. The wafer of the shadow mask 168 is then attached to the substrate 140 with alignment marks matched so as to locate the aperture 166 over the desired location on the top electrode 164 for the tip 169. After, the shadow mask is in place, 5-10 microns of the desired tip material, e.g., niobium or tantalum, are deposited through the aperture 166 to form the tip 169. Note, that in the preferred embodiment, the structure of Figure 32 will be formed at multiple locations on the wafer, and only one shadow mask 168 will be used with multiple apertures at all the desired tip locations for all the cantilevers. Finally, the shadow mask is carefully removed so as to not damage the tips.

Next, the cantilevers are separated from the substrate along part of their length. Figure 33 shows the structure after this process has been performed. Separation is accomplished by depositing 10 microns of positive resist on side A of the wafer to protect the structure just described. The wafer is then subjected to a backside etch to etch through the remaining silicon membrane at the bottom of the pit 142 by subjecting side B of the wafer to a 3:1  $SF_6:C_2ClF_5$  plasma etch. The details of this etch are specified in Appendix A. The photoresist is then stripped using acetone, methanol and an air dry cycle. The individual die are then separated by cracking the wafer along the scribe lines.

The presence of the silicon dioxide layer 136 has been found to promote better growth of the aluminum layer 148 which also improves the growth of zinc oxide layers 152 and 160. It also allows conductive paths to

be formed beneath the cantilever without being shorted out by the metal of the layer 148. The presence of the silicon dioxide layers 150 and 158 promotes better growth of the zinc oxide layers 152 and 160. The presence of the silicon dioxide layers 154 and 162 aids in balancing stresses in the cantilever which can build up during the deposition processes of forming the cantilever. That is, the same stresses will build up in the silicon dioxide layers 154 and 162 when they are deposited as build up in the silicon dioxide layers 150 and 158 when they are deposited. Accordingly, the stresses are balanced. Also, the silicon dioxide layers separating the pairs of electrodes increases the breakdown voltage. In alternative embodiments, the silicon dioxide layers may be omitted or other materials can be substituted.

The preferred method just described can be used to make either the "one-arm" or bipod type of piezoelectric transducer. The principal difference between these two different structures is in the number of electrode pairs that are formed inside each integrated cantilever. The one arm type of bimorph needs to have at least four pairs of electrodes formed to obtain 3 axis movement. If the one arm type of integrated transducer is to be used for a scanning tunneling microscope, 6 pairs of electrodes must be formed so that electrical connection can be made to the tip and the spurious piezo effects by this tip electrode can be cancelled out. For a two arm bipod type of transducer, only two pairs of electrodes need be formed in each bimorph arm. Obvious modifications to the above described process for the steps of forming the top electrode 148 and the bottom electrode 164 can be made depending upon the type of integrated piezoelectric transducer to be fabricated.

Referring to Figures 34(a) and (b) through 36(a) and (b) there are illustrated the movements which may be achieved with a one arm bimorph integrated piezoelectric transducer with the electrode structure shown in Figure 10. The (a) and (b) illustrations of each figure depict both the positive and negative movements on the associated axis. Figure 37(a) and (b) illustrate the type of rotational movement which may be achieved for two tip embodiments to have independent Z-axis movement for each tip. The tips move together along the Y and X axes however.

Typical performance parameters are as follows. If a dipod structure is considered with aluminum electrodes one micron thick and zinc oxide layers which are two microns thick, and the legs are each 1000 microns long and 100 microns wide, then the bipod will be able to move the tip 20 angstroms per volt in the X and Y axes and 0.6 microns per volt in the Z axis. The breakdown voltage is 30 volts and the scannable area is 600 angstroms by 600 angstroms or 360,000 square angstroms. If a single arm cantilever bimorph with the same dimensions as given in this paragraph is considered, 200 angstroms per volt of movement in the X axis and 20 angstroms per volt in the Y axis can be achieved. Movement of 0.6 angstroms per volt in the Z axis can be achieved. Thus, the scannable area for the single arm bimorph is 10 times larger than the dipod since the X axis movement is ten times greater per volt. The bimorph design must be such that the tip can be moved within tunneling range of the conductive surface for STM applications.

## Preferred Planar STM Process

- 5 1. Deposition of mask materials
  - 1a. Clean 380  $\mu\text{m}$  thick (100) wafer using standard acid clean\*\*\*
  - 1b. Thermally grow 5000  $\text{\AA}$   $\text{SiO}_2$
  - 1c. Deposit 1000 $\text{\AA}$   $\text{Si}_3\text{N}_4$  using LPCVD
- 10 2. Etch KOH pits from backside (rough surface, side B)
  - 2a. Using mask #1 and negative photoresist, define KOH squares
  - 2b. Oxygen plasma\* for 1 min to 'Descum' openings
  - 2c. Etch  $\text{Si}_3\text{N}_4$  using  $\text{SF}_6$  and F13B1 (1:1) plasma etch
  - 2d. Etch  $\text{SiO}_2$  layer using 6:1 buffered Oxide Etch (BOE)
  - 2e. Strip photoresist and clean wafer\*\*
  - 15 2e. Etch 340  $\mu\text{m}$  of silicon from backside using 30% KOH at 80°C
  - 2f. Rinse wafer using 10:1  $\text{H}_2\text{O}:\text{HCl}$  solution
  - 2g. Rinse in de-ionized water (DI) then dry in  $\text{N}_2$
- 20 3. Etch Alignment marks on frontside (polished side, side A)
  - 3a. Using mask #2 and positive resist, define alignment marks
  - 3b. Oxygen plasma\* for 1 min to 'Descum' openings
  - 3c. Etch  $\text{Si}_3\text{N}_4$  using  $\text{SF}_6$  and F13B1 (1:1) plasma\* etch
  - 3d. Etch  $\text{SiO}_2$  layer using 6:1 buffered Oxide Etch (BOE)
  - 3e. Rinse in DI then dry in  $\text{N}_2$
  - 25 3f. Etch 3  $\mu\text{m}$  of Si using 1:1  $\text{SF}_6:\text{C}_2\text{ClF}_5$  plasma etch
  - 3g. Clean wafer using standard acid clean (strip resist)\*\*
  - 3h. Strip  $\text{Si}_3\text{N}_4$  using concentrated  $\text{H}_3\text{PO}_4$  @ 165°C for 1 hr
  - 3i. Rinse in DI then dry in  $\text{N}_2$
- 30 4. Deposit bottom electrodes
  - 4a. Define pattern w/ mask #3, positive resist and liftoff process
  - 4b. E-beam evaporate 1000 $\text{\AA}$  Al using room temp. wafer holder
  - 4c. "Liftoff" excess Al by soaking wafer in hot Acetone
  - 4d. Rinse wafer in fresh Acetone, Methanol, and DI, then dry in  $\text{N}_2$
- 35 5. Deposit lower oxides
  - 5a. Sputter clean surface, 30 sec
  - 5b. E-beam evaporate 1000 $\text{\AA}$   $\text{SiO}_2$  substrate is heated to 200°C
  - 5c. Sputter deposit 2 $\mu\text{m}$  ZnO using Zn target in 5:1  $\text{O}_2:\text{Ar}$  gas, 30mTorr.  
Substrate held to 300°C
  - 40 5d. E-beam evaporate 1000 $\text{\AA}$   $\text{SiO}_2$  substrate is heated to 200°C
- 40 6. Deposit middle electrodes
  - 6a. Define pattern w/ mask #4, positive resist and liftoff process
  - 6b. E-beam evaporate 1000 $\text{\AA}$  Al using cold wafer holder
  - 6c. "Liftoff" excess Al by soaking wafer in hot Acetone
  - 6d. Rinse wafer in fresh Acetone, Methanol, and DI, then dry in  $\text{N}_2$
- 45 7. Deposit upper oxides
  - 7a. Sputter clean surface, 30 sec
  - 7b. E-beam evaporate 1000 $\text{\AA}$   $\text{SiO}_2$  substrate is held to 200°C
  - 7c. Sputter deposit 2 $\mu\text{m}$  ZnO using Zn target in 5:1  $\text{O}_2:\text{Ar}$  gas, 30mTorr.  
Substrate held to 300°C
  - 50 7d. E-beam evaporate 1000 $\text{\AA}$   $\text{SiO}_2$  substrate is held to 200°C
- 55 8. Deposit Top electrodes

- 5  
8a. Define pattern w/ mask #5, positive resist and liftoff process  
8b. E-beam evaporate 500Å Al using room temp. wafer holder  
8c. E-beam evaporate 500Å Au (Gold) using room temp. wafer holder  
8d. "Liftoff" excess Al and Au by soaking wafer in hot Acetone  
8e. Rinse wafer in fresh Acetone, Methanol, and DI, then dry in N<sub>2</sub>
- 10  
9. Pattern ZnO  
9a. Sputter deposit 3000Å Ti/W using room temp. wafer holder  
9b. Define pattern w/ mask #6, positive resist  
9c. Pattern Ti/W using 30% H<sub>2</sub>O<sub>2</sub>, 30 min @ room temp.  
9d. Rinse in DI then dry in N<sub>2</sub>  
9e. Etch top layer SiO<sub>2</sub> using 6:1 BOE (1 min), Rinse in DI  
9f. Etch upper ZnO in following solution: 15 g NaNO<sub>3</sub>, 5ml HNO<sub>3</sub>, 600 ml H<sub>2</sub>O, Rinse in DI  
15  
9g. Etch middle layer SiO<sub>2</sub> using 6:1 BOE (2 min), Rinse in DI  
9h. Etch lower ZnO in following solution: 15 g NaNO<sub>3</sub>, 5ml HNO<sub>3</sub>, 600 ml H<sub>2</sub>O, Rinse in DI  
9i. Etch bottom layer SiO<sub>2</sub> using 6:1 BOE (1 min),  
9j. Rinse in DI then dry in N<sub>2</sub>  
20  
9k. Etch 3 µm of Si using 1:1 SF<sub>6</sub>:C<sub>2</sub>ClF<sub>5</sub> plasma etch  
9l. Clean wafer, strip resist using Acetone, Methanol, and DI  
9m. Strip Ti/W in 30% H<sub>2</sub>O<sub>2</sub> (30 min @ room temp.)  
9n. Rinse in DI then dry in N<sub>2</sub>
- 25  
10. Deposit bonding pad metal  
10a. Define pattern w/ mask #7, positive resist and liftoff process  
10b. E-beam evaporate 1.0µm Al using room temp. wafer holder  
10c. "Liftoff" excess Al by soaking wafer in hot Acetone  
10d. Rinse wafer in fresh Acetone, Methanol, and DI then dry in N<sub>2</sub>
- 30  
11. Scribe wafers on Side B using saw
- 35  
12. Deposit Tips  
12a. Sputter clean surface for 30 seconds  
12b. Place shadow mask on top of wafer, align to pattern using 'key' formed with Al/ZnO/Al/ZnO/Au pattern  
12c. Deposit 5-10 µm Niobium, forming pointed tips  
12d. Carefully remove shadow mask, avoid damaging tips
- 40  
13. Separate cantilevers from substrate  
13a. Deposit 10 µm layer positive resist on Side A  
13b. Etch through Si membrane from side B using 3:1 SF<sub>6</sub>:C<sub>2</sub>ClF<sub>5</sub> Plasma\* etch  
13c. Strip photoresist in Acetone & Methanol, air dry
- 45  
14. Separate dies (or 'chips') by cracking wafer along scribe lines  
\* All plasma etches are performed using Power = 500W at 200 mTorr pressure for 6 min, unless otherwise stated  
\*\* Standard clean for removing negative photoresist  
\*\*a. Agitate vigorously in 120°C 10:1 H<sub>2</sub>SO<sub>4</sub>:H<sub>2</sub>O<sub>2</sub> for 20 min  
\*\*b. Rinse in DI  
\*\*c. Soak in 4:1:1 H<sub>2</sub>O:H<sub>2</sub>SO<sub>4</sub>:H<sub>2</sub>O<sub>2</sub> at 90°C for 20 min  
\*\*d. Rinse in DI then dry in N<sub>2</sub>
- 50  
\*\*\* Standard Pre-Oxidation Clean  
\*\*\*a. Perform above clean (\* Standard clean for removing negative photoresist)
- 55

ends and respective second ends that are joined together, said tip located proximate where said respective second ends are joined, each said bimorph cantilever arm including one electrode of said first plurality of electrodes and one electrode of said second plurality of electrodes.

- 5 6. A method of forming an integrated scanning tunneling microscope comprising:
  - fabricating a motion transducer integrally with a substrate;
  - growing on said motion transducer a protruding conductive tip (66), terminating in a point;
  - positioning a conductive surface (84) at a fixed position close to said conductive tip (66) such that
  - 10 movement of said motion transducer is sufficient to bring said conductive tip within tunneling range of said conductive surface;
  - providing bias means (22) for applying a bias potential between said tip and said conductive surface to cause tunneling current to flow between said tip and said conductive surface; and
  - providing sensing means (24) for sensing the magnitude of the tunneling current flow;
  - characterized by:
  - 15 said motion transducer fabricating step fabricating a piezoelectric bimorph cantilever integrally with said substrate at one end with said tip positioned at a second end of said cantilever, including the steps of
    - depositing a first conductive layer on said substrate and patterning said first conductive layer into
    - 20 a first plurality of electrodes (36, 38, 40);
    - depositing a first layer of piezoelectric material (42) over said first conductive layer;
    - depositing a second conductive layer (44) over said first layer of piezoelectric material;
    - depositing a second layer of piezoelectric material (46) over said second conductive layer;
    - depositing a third conductive layer over said second layer of piezoelectric material and patterning
    - 25 said third conductive layer into a second plurality of electrodes (48, 50, 52);
    - removing a portion of said substrate from below said first conductive layer such that said bimorph cantilever has said one end attached to said substrate and said second end in free space; and
    - providing control means (28), coupled to said bias means, sensing means and said electrodes, for adjusting the potentials applied to said electrodes so as to move said tip.
- 30 7. The method of forming an integrated scanning tunneling microscope of Claim 6, further characterized by:
  - said positioning step including depositing a second substrate (82) having a cavity (86) formed therein and having said conductive surface (84) in said cavity, and attaching said second substrate (82)
  - 35 to said substrate (32) so as to place said cavity such that said bimorph cantilever has room to move in all three axes and such that said conductive surface is held close to said tip such that said bimorph cantilever's range of motion is sufficient to bring said tip within tunneling range of said conductive surface.
8. The method of forming an integrated scanning tunneling microscope of Claims 6 or 7, further characterized by:
  - 40 said growing step comprising growing said tip on said bimorph cantilever by evaporation of conductive material through a shadow mask having an aperture (166) aligned over said second end of said bimorph cantilever.
9. The method of forming an integrated scanning tunneling microscope of Claims 6 or 7, further characterized by:
  - 45 said bimorph cantilever fabricating step beginning with depositing a sacrificial spacer layer over a part of said substrate where a cantilevered portion of said bimorph cantilever will be fabricated; and
  - said removing step including removing said sacrificial spacer layer so as to produce said cantilever with said one end attached and said second end in free space.
- 50 10. The method of forming an integrated scanning tunneling microscope of Claims 6 or 7, further characterized by:
  - said piezoelectric bimorph cantilever fabricating step beginning with etching a portion of said substrate to form a thin membrane of material, said subsequent steps of depositing conductive and piezoelectric layers including positioning at least some of said electrodes over said thin membrane of material.
- 55 11. The method of forming an integrated scanning tunneling microscope of Claims 6 or 7, further characterized by:
  - said piezoelectric bimorph cantilever fabricating step including fabricating two piezoelectric bimorph cantilever arms having distinct fixed ends and respective second ends that are joined together,



- \*\*\*b. Soak in 10:1:1 H<sub>2</sub>O:HCl:H<sub>2</sub>O<sub>2</sub> at 90°C for 20 min
- \*\*\*c. Rinse in DI
- \*\*\*d. Soak in 10:1:1 H<sub>2</sub>O:NH<sub>4</sub>OH:H<sub>2</sub>O<sub>2</sub> at 90°C for 20 min
- \*\*\*e. Rinse in DI
- \*\*\*f. Dip in 50:1 BOE for 30 sec at 23°C (ambient)
- \*\*\*g. Rinse in DI then dry in N<sub>2</sub>

# Claims

1. An integrated scanning tunneling microscope comprising:
  - a motion transducer integrated on a substrate (32) and having a protruding conductive tip (66), terminating in a point;
  - means coupled to said motion transducer for holding a conductive surface (84) at a fixed position close to said conductive tip (66) such that movement of said motion transducer is sufficient to bring said conductive tip within tunneling range of said conductive surface;
  - bias means (22) for applying a bias potential between said tip and said conductive surface sufficient to cause tunneling current to flow between said tip and said conductive surface;
  - sensing means (24) for sensing the magnitude of the tunneling current flow; and
  - control means (28), coupled to said bias means and said motion transducer to position said tip so as to adjust said tunneling current;
  - characterized by:
    - said motion transducer comprising a three-axis movement piezoelectric bimorph cantilever attached to said substrate at one end with said tip positioned at a second end of said cantilever, said bimorph cantilever including a first plurality of electrodes (36, 38, 40), a second plurality of electrodes (48, 50, 52), two layers of piezoelectric material (42, 46) sandwiched between said first and second plurality of electrodes, and an electrode (44) sandwiched between said two layers of piezoelectric material; wherein said bimorph cantilever moves in response to potentials applied to said electrodes; and
    - said control means (28) including means for apply voltage potentials to said electrodes of said bimorph cantilever so as to move said tip.
2. The integrated scanning tunneling microscope of Claim 1, further characterized by:
  - said means for holding said conductive surface comprising a second substrate (82) having a cavity (86) formed therein and having said conductive surface (84) in said cavity, said second substrate (82) attached to said substrate (32) so as to place said cavity such that said bimorph cantilever has room to move in all three axes and such that said conductive surface is held close to said tip such that said cantilever's range of motion is sufficient to bring said tip within tunneling range of said conductive surface.
3. The integrated scanning tunneling microscope of Claims 1 or 2, further characterized by:
  - said bimorph cantilever including:
    - a first conductive layer patterned to form said first plurality of electrodes (36, 38, 40);
    - a first layer of piezoelectric material (42) formed over said first conductive layer;
    - a second conductive layer (44) formed over said first layer of piezoelectric material and comprising said electrode (44);
    - a second layer of piezoelectric material (46) formed over said second conductive layer; and
    - a third conductive layer formed over said second layer of piezoelectric material, said third conductive layer patterned to form said second plurality of electrodes (48, 50, 52) aligned with said first plurality of electrodes patterned in said first conductive layer.
4. The integrated scanning tunneling microscope of Claim 1, further characterized by:
  - said tip having the physical shape, orientation and size characteristic of an integrated tip structure formed by evaporation of conductive material through a shadow mask having an aperture (166) aligned over said second end of said cantilever.
5. The integrated scanning tunneling microscope of Claims 1, 2, 3, or 4 further characterized by:
  - said bimorph cantilever comprising two piezoelectric bimorph cantilever arms having distinct fixed

each said bimorph cantilever arm being fabricated to include one electrode of said first plurality of electrodes and one electrode of said second plurality of electrodes.

5 Patentansprüche

1. Integriertes abtastendes Tunnelmikroskop mit  
einem auf ein Substrat (32) integriertem Bewegungswandler mit einer vorstehenden leitfähigen Spitze (66), die punktförmig endet  
10 einer mit dem Bewegungswandler gekoppelten Einrichtung zum Halten einer leitfähigen Oberfläche (84) an einer festen Stellung in der Nähe der leitfähigen Spitze (66) derart, daß eine Bewegung des Bewegungswandlers ausreicht, die leitfähige Spitze in den Tunnelbereich der leitfähigen Oberfläche zu bringen,  
eine Vorspanneinrichtung (22) zum Anlegen eines Vorspannpotentials zwischen Spitze und leitfähiger Fläche, das ausreicht, einen Tunnelstrom zwischen der Spitze und der leitfähigen Oberfläche fließen zu lassen,  
15 eine Fühleinrichtung (24) zum Erfassen der Größe des Tunnelstromes und  
eine Steuereinrichtung (28), die an die Vorspanneinrichtung und den Bewegungswandler derart gekoppelt ist, daß die Spitze so positioniert wird, daß der Tunnelstrom einstellbar ist,  
20 dadurch gekennzeichnet  
daß der Bewegungswandler einen in Richtung von drei Achsen beweglichen piezoelektrischen bimorphen Ausleger aufweist, der mit einem Ende am Substrat befestigt ist und am zweiten Ende die Spitze trägt, wobei der bimorphe Ausleger eine erste Anzahl von Elektroden (36, 38, 40) und eine zweite Anzahl von Elektroden (48, 50, 52), zwei Schichten aus piezoelektrischem Material (42, 46), die zwischen  
25 der ersten und zweiten Anzahl von Elektroden schichtweise angeordnet sind, und eine Elektrode (44) umfaßt, die zwischen die beiden Schichten aus piezoelektrischem Material geschichtet ist, wobei sich der bimorphe Ausleger auf an die Elektroden angelegte Potentiale bewegt, und  
daß die Steuereinrichtung (28) zum Bewegen der Spitze eine Einrichtung zum Anlegen von Spannungspotentialen an die Elektroden des bimorphen Auslegers umfaßt.  
30
2. Tunnelmikroskop nach Anspruch 1, dadurch gekennzeichnet,  
daß die Einrichtung zum Halten der leitfähigen Oberfläche ein zweites Substrat (82) mit einer darin ausgebildeten Aushöhlung (86) aufweist, in der die leitfähige Oberfläche (84) vorgesehen ist, daß das  
35 zweite Substrat (82) am Substrat (32) derart befestigt ist, daß die Aushöhlung derart plaziert wird, daß der bimorphe Ausleger in allen drei Achsen beweglich ist und derart, daß die leitfähige Oberfläche nahe an der Spitze gehalten wird, so daß der Bewegungsbereich des Auslegers ausreicht, die Spitze in den Tunnelbereich der leitfähigen Oberfläche zu bringen.
3. Tunnelmikroskop nach Anspruch 1 oder 2, dadurch gekennzeichnet, daß der bimorphe Ausleger umfaßt:  
40 eine derart gemusterte erste leitfähige Schicht, daß die erste Anzahl von Elektroden (36, 38, 40) gebildet wird,  
eine erste Schicht (42) aus piezoelektrischem Material, die über der ersten leitfähigen Schicht gebildet ist,  
eine zweite leitfähige Schicht (44), die über der ersten Schicht aus piezoelektrischem Material gebildet ist und die Elektrode (44) aufweist,  
45 eine zweite, über der zweiten leitfähigen Schicht gebildete Schicht aus piezoelektrischem Material (46) und  
eine dritte über der zweiten Schicht aus piezoelektrischem Material gebildete leitfähige Schicht, die so gemustert ist, daß die zweite Anzahl von Elektroden (48, 50, 52) ausgerichtet auf die erste Anzahl von in der ersten leitfähigen Schicht gemusterten Elektroden ausgebildet wird.  
50
4. Tunnelmikroskop nach Anspruch 1, dadurch gekennzeichnet, daß die Spitze die physikalische Form, Ausrichtung und Größe einer integrierten Spitzenstruktur aufweist, die durch Aufdampfen leitfähigen Materials durch eine Schattenmaske gebildet ist, wobei die Maske eine über dem zweiten Ende des Auslegers ausgerichtete Öffnung (166) aufweist.  
55
5. Mikroskop nach Anspruch 1, 2, 3 oder 4, dadurch gekennzeichnet, daß der bimorphe Ausleger zwei piezoelektrische bimorphe Auslegerarme aufweist, die distinkte feste Enden und jeweils miteinander verbun-

dene zweite Enden aufweisen, wobei die Spitze in der Nähe des Verbindungspunktes der bimorphen Auslegerarme verbunden sind und eine der Elektroden der ersten Elektrodenzahl und eine Elektrode der zweiten Elektrodenzahl aufweisen.

- 5 6. Verfahren zum Herstellen eines integrierten abtastenden Tunnelmikroskops mit folgenden Schritten:  
 Herstellen eines Bewegungswandlers einteilig mit einem Substrat,  
 Aufwachsen einer vorspringenden Spitze (66), die in einem Punkt endet,  
 Anordnen einer leitfähigen Oberfläche (84) an einer festen Stelle in der Nähe der leitfähigen Spitze  
 (66) derart, daß eine Bewegung des Bewegungswandlers ausreicht, die leitfähige Spitze in den Tunnel-  
 10 bereich der leitfähigen Oberfläche zu bringen,  
 Vorsehen einer Vorspanneinrichtung (22) zum Anlegen eines Vorspannpotentials zwischen Spitze  
 und leitfähiger Oberfläche, um einen Tunnelstrom zwischen Spitze und leitfähiger Oberfläche fließen zu  
 lassen, und Vorsehen einer Fühleinrichtung (24) zum Erfassen der Größe des Tunnelstromes,  
 dadurch gekennzeichnet, daß  
 15 die Herstellung des Bewegungswandlers die Herstellung eines piezoelektrischen bimorphen Aus-  
 legers umfaßt, der mit einem Ende mit dem Substrat einteilig verbunden ist und an seinem anderen Ende  
 die Spitze trägt, mit den Schritten:  
 Ablagern einer ersten leitfähigen Schicht auf dem Substrat und Mustern der ersten leitfähigen  
 Schicht in eine erste Anzahl von Elektroden (36, 38, 40),  
 20 Ablagern einer ersten Schicht (42) aus piezoelektrischem Material über der leitfähigen Schicht,  
 Ablagern einer zweiten leitfähigen Schicht (44) über der ersten Schicht aus piezoelektrischem Ma-  
 terial,  
 Ablagern einer zweiten Schicht (46) aus piezoelektrischem Material über der zweiten leitfähigen  
 Schicht,  
 25 Ablagern einer dritten leitfähigen Schicht über der zweiten Schicht aus piezoelektrischem Material  
 und Mustern der dritten leitfähigen Schicht in eine zweite Anzahl von Elektroden (48, 50, 52),  
 Entfernen eines Teils des Substrats von unterhalb der ersten leitfähigen Schicht derart, daß der  
 bimorphe Ausleger mit einem Ende am Substrat befestigt ist und das zweite Ende frei endet und  
 Vorsehen einer Steuereinrichtung, die mit der Vorspanneinrichtung, der Fühleinrichtung und den  
 30 Elektroden gekoppelt ist, zum Einstellen der an die Elektrode angelegten Potentiale und zum Bewegen  
 der Spitze.
7. Verfahren nach Anspruch 6, dadurch gekennzeichnet, daß der Positionierschritt das Ablagern eines zwei-  
 35 ten Substrats (82) mit einer darin ausgebildeten Aushöhlung (86) umfaßt, wobei sich die leitfähige Ober-  
 fläche (84) in der Aushöhlung befindet, und  
 Befestigen des zweiten Substrats (82) am Substrat (32) derart, daß die Aushöhlung so angeordnet  
 wird, daß der bimorphe Ausleger in allen drei Achsen beweglich ist und daß die leitfähige Oberfläche in  
 der Nähe der Spitze derart gehalten wird, daß der Bewegungsbereich des Auslegers ausreicht, die Spitze  
 in den Tunnelbereich der leitfähigen Oberfläche zu bringen.
- 40 8. Verfahren nach Anspruch 6 oder 7, dadurch gekennzeichnet, daß beim Aufwachsen die Spitze auf dem  
 bimorphen Ausleger durch Aufdampfen leitfähigen Materials durch eine Schattenmaske aufgewachsen  
 wird, wobei die Schattenmaske eine Öffnung (166) aufweist, die über dem zweiten Ende des bimorphen  
 Auslegers ausgerichtet ist.
- 45 9. Verfahren nach Anspruch 6 oder 7, dadurch gekennzeichnet,  
 daß der Schritt der Herstellung des bimorphen Auslegers mit dem Ablagern einer Verbrauchs -Ab-  
 standsschicht über einem Teil des Substrats beginnt, wo ein eingespannter Teil des bimorphen Auslegers  
 hergestellt wird und,  
 50 daß der Schritt des Entferns das Entfernen der Verbrauchs-Abstandsschicht derart umfaßt, daß  
 der Ausleger mit einem befestigten und einem zweiten freien Ende hergestellt wird.
10. Verfahren nach Anspruch 6 oder 7, dadurch gekennzeichnet, daß der Schritt der Herstellung des piezo-  
 elektrischen bimorphen Auslegers mit dem Ätzen eines Teils des Substrats derart beginnt, daß eine dün-  
 55 ne Materialmembran gebildet wird, wobei die nachfolgenden Schritte des Ablagerns leitfähiger und pie-  
 zoelektrischer Schichten das Positionieren wenigstens einiger der Elektroden über der dünnen Material-  
 membran umfaßt.
11. Verfahren nach Anspruch 6 oder 7, dadurch gekennzeichnet, daß der Schritt der Herstellung des piezo-

elektrischen bimorphen Auslegers die Herstellung zweier piezoelektrischer bimorpher Auslegerarme umfaßt, die distinkte feste Enden und jeweils miteinander verbundene zweite Enden aufweisen, wobei der bimorphe Auslegerarm so hergestellt wird, daß er eine Elektrode der ersten Elektrodenanzahl und eine Elektrode der zweiten Elektrodenanzahl aufweist.

5

## Revendications

1. Microscope intégré à balayage à effet tunnel comprenant:
  - un transducteur de mouvement intégré sur un substrat (32) et ayant une pointe (66) conductrice en saillie, se terminant en un point;
  - des moyens couplés audit transducteur de mouvement pour maintenir une surface conductrice (84) dans une position fixe proche de ladite pointe conductrice (66) de telle sorte que le déplacement dudit transducteur de mouvement est suffisant pour placer ladite pointe conductrice dans la plage à effet tunnel de ladite surface conductrice;
  - des moyens de polarisation (22) pour appliquer un potentiel de polarisation entre ladite pointe et ladite surface conductrice, suffisant pour conduire le courant par effet tunnel à circuler entre ladite pointe et ladite surface conductrice;
  - des moyens de détection (24) pour détecter l'intensité de la circulation du courant par effet tunnel;
  - et
  - des moyens de commande (28), couplés auxdits moyens de polarisation et audit transducteur de mouvement pour positionner ladite pointe de manière à régler ledit courant par effet tunnel;
  - caractérisé en ce que:
    - ledit transducteur de mouvement comporte un élément en porte-à-faux bimorphe piézoélectrique à déplacement selon trois axes fixé audit substrat à une extrémité, ladite pointe étant positionnée à une seconde extrémité de l'élément en porte-à-faux, ledit élément en porte-à-faux bimorphe comportant une première pluralité d'électrodes (36, 38, 40), une seconde pluralité d'électrodes (48, 50, 52), deux couches de matériau piézoélectrique (42, 46) prises en sandwich entre lesdites première et seconde pluralité d'électrodes, et une électrode (44) prise en sandwich entre lesdites deux couches de matériau piézoélectrique; dans lequel ledit élément en porte-à-faux bimorphe se déplace en réponse à des potentiels appliqués auxdites électrodes; et
    - lesdits moyens de commande (28) comportent des moyens pour appliquer des potentiels de tension auxdites électrodes dudit élément en porte-à-faux bimorphe de manière à déplacer ladite pointe.
2. Microscope intégré à balayage à effet tunnel selon la revendication 1, caractérisé en outre en ce que:
  - lesdits moyens pour maintenir ladite surface conductrice comportent un second substrat (82) ayant une cavité (86) formée dans celui-ci, ladite surface conductrice (84) étant dans ladite cavité, ledit second substrat (82) étant fixé audit substrat (32) de manière à disposer ladite cavité de telle sorte que ledit élément en porte-à-faux bimorphe a de la place pour se déplacer selon les trois axes et de telle sorte que ladite surface conductrice est maintenue près de ladite pointe de telle sorte que la plage de déplacement dudit élément en porte-à-faux est suffisante pour placer ladite pointe à l'intérieur de la plage à effet tunnel de ladite surface conductrice.
3. Microscope intégré à balayage à effet tunnel selon les revendications 1 ou 2, caractérisé en outre en ce que:
  - ledit élément en porte-à-faux bimorphe comporte:
    - une première couche conductrice configurée pour former ladite première pluralité d'électrodes (36, 38, 40);
    - une première couche de matériau piézoélectrique (42) formée sur ladite première couche conductrice;
    - une seconde couche conductrice (44) formée sur ladite première couche de matériau piézoélectrique et comprenant ladite électrode (44);
    - une seconde couche de matériau piézoélectrique (46) formée sur ladite seconde couche conductrice; et
    - une troisième couche conductrice formée sur ladite seconde couche de matériau piézoélectrique, ladite troisième couche conductrice configurée pour former ladite seconde pluralité d'électrodes (48, 50, 52) étant alignée avec ladite première pluralité d'électrodes configurées dans ladite première couche conductrice.

4. Microscope intégré à balayage à effet tunnel selon la revendication 1, caractérisé en outre en ce que:  
ladite pointe a la forme physique, l'orientation et les dimensions caractéristiques d'une structure en pointe intégrée formée par évaporation de matériau conducteur à travers un masque perforé muni d'une ouverture (166) alignée sur ladite seconde extrémité dudit élément en porte-à-faux.

5. Microscope intégré à balayage à effet tunnel selon les revendications 1, 2, 3 ou 4, caractérisé en outre en ce que:

ledit élément en porte-à-faux bimorphe comporte deux bras en porte-à-faux bimorphes piézoélectriques ayant des extrémités fixes distinctes et des secondes extrémités respectives qui sont reliées les unes aux autres, ladite pointe étant située à proximité de l'endroit où lesdites secondes extrémités respectives sont reliées, chaque bras en porte-à-faux bimorphe comportant une électrode de ladite première pluralité d'électrodes et une électrode de ladite seconde pluralité d'électrodes.

6. Procédé de formation d'un microscope intégré à balayage à effet tunnel comprenant:

la fabrication d'un transducteur de mouvement faisant corps avec un substrat;

la croissance sur ledit transducteur de mouvement d'une pointe conductrice (66) en saillie, se terminant en un point;

le positionnement d'une surface conductrice (84) dans une position fixe proche de ladite pointe conductrice (66) de telle sorte que le déplacement dudit transducteur de mouvement est suffisant pour placer ladite pointe conductrice à l'intérieur de la plage d'effet tunnel de ladite surface conductrice;

la fourniture d'un moyen de polarisation (22) pour appliquer un potentiel de polarisation entre ladite pointe et ladite surface conductrice pour conduire le courant par effet tunnel à circuler entre ladite pointe et ladite surface conductrice; et

la fourniture de moyens de détection (24) pour détecter l'intensité de la circulation du courant par effet tunnel;

caractérisé en ce que:

ladite étape de fabrication du transducteur de mouvement réalise un élément en porte-à-faux bimorphe piézoélectrique faisant corps avec ledit substrat à une extrémité avec ladite pointe positionnée à une seconde extrémité dudit élément en porte-à-faux, comprenant les étapes suivantes:

dépôt d'une première couche conductrice sur ledit substrat et configuration de ladite première couche conductrice en une première pluralité d'électrodes (36, 38, 40);

dépôt d'une première couche de matériau piézoélectrique (42) sur ladite première couche conductrice;

dépôt d'une seconde couche conductrice (44) sur ladite première couche de matériau piézoélectrique;

dépôt d'une seconde couche de matériau piézoélectrique (46) sur ladite seconde couche conductrice;

dépôt d'une troisième couche conductrice sur ladite seconde couche de matériau piézoélectrique et configuration de ladite troisième couche conductrice en une seconde pluralité d'électrodes (48, 50, 52);

retrait d'une partie dudit substrat depuis le dessous de ladite première couche conductrice de telle sorte que ledit élément en porte-à-faux bimorphe a ladite extrémité fixée audit substrat et ladite seconde extrémité libre dans l'espace; et

fourniture de moyens de commande (28), couplés auxdits moyens de polarisation, auxdits moyens de détection et auxdites électrodes, pour régler les potentiels appliqués auxdites électrodes de manière à déplacer ladite pointe.

7. Procédé de formation d'un microscope intégré à balayage à effet tunnel selon la revendication 6, caractérisé en outre en ce que:

ladite étape de positionnement comporte le dépôt d'un second substrat (82) ayant une cavité (86) formée dans celui-ci et ayant ladite surface conductrice (84) dans ladite cavité, et la fixation dudit second substrat (82) audit substrat (32) de manière à placer ladite cavité de telle sorte que ledit élément en porte-à-faux bimorphe a la place de se déplacer selon les trois axes et de telle sorte que ladite surface conductrice est maintenue près de ladite pointe de telle sorte que la plage de déplacement de l'élément en porte-à-faux bimorphe est suffisante pour placer ladite pointe à l'intérieur de la plage à effet tunnel de ladite surface conductrice.

8. Procédé de formation d'un microscope intégré à balayage à effet tunnel selon les revendications 6 ou 7, caractérisé en outre en ce que:

ladite étape de croissance comporte la croissance de ladite pointe sur ledit élément en porte-à-faux bimorphe par évaporation de matériau conducteur à travers un masque perforé muni d'une ouverture (166) alignée sur ladite seconde extrémité dudit élément en porte-à-faux bimorphe.

- 5 9. Procédé de formation d'un microscope intégré à balayage à effet tunnel selon les revendications 6 ou 7, caractérisé en outre en ce que:

ladite étape de fabrication de l'élément en porte-à-faux bimorphe commence par le dépôt d'une couche d'entretoise sacrifiée sur une partie dudit substrat où une partie en porte-à-faux dudit élément en porte-à-faux bimorphe sera fabriquée; et

- 10 ladite étape de retrait comporte le retrait de ladite couche d'entretoise sacrifiée de manière à produire ledit élément en porte-à-faux avec ladite extrémité fixée et ladite seconde extrémité libre dans l'espace.

- 15 10. Procédé de formation d'un microscope intégré à balayage à effet tunnel selon les revendications 6 ou 7, caractérisé en outre en ce que:

ladite étape de fabrication dudit élément en porte-à-faux bimorphe piézoélectrique commence par l'attaque d'une partie dudit substrat pour former une fine membrane de matériau, lesdites étapes ultérieures de dépôt des couches conductrices et piézoélectriques comportant le positionnement d'au moins certaines desdites électrodes sur ladite fine membrane de matériau.

- 20 11. Procédé de formation d'un microscope intégré à balayage à effet tunnel selon les revendications 6 ou 7, caractérisé en outre en ce que:

ladite étape de fabrication dudit élément en porte-à-faux bimorphe piézoélectrique comporte la fabrication de deux bras en porte-à-faux bimorphes piézoélectriques ayant des extrémités fixes distinctes et des secondes extrémités respectives qui sont reliées les unes aux autres, chacun desdits bras en porte-à-faux bimorphe étant fabriqué pour comporter une électrode de ladite première pluralité d'électrodes et une électrode de ladite seconde pluralité d'électrodes.

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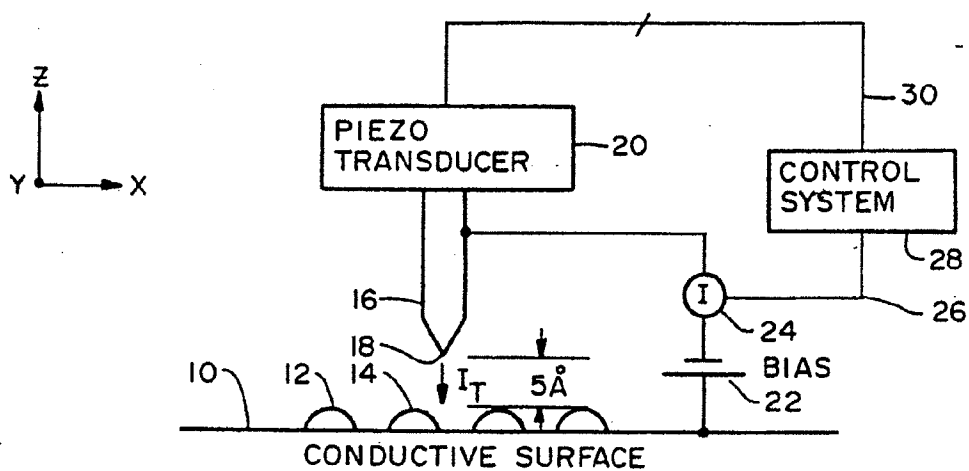


FIG. 1

PRIOR ART

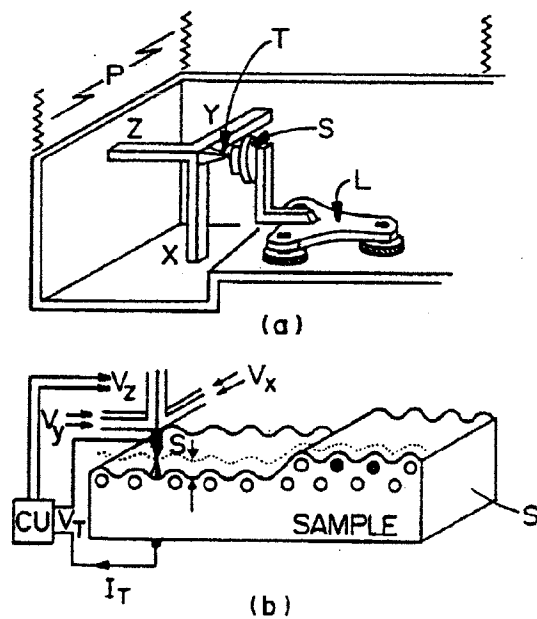


FIG. 2

PRIOR ART

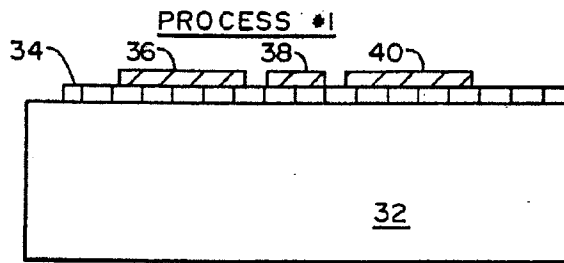


FIG. 3

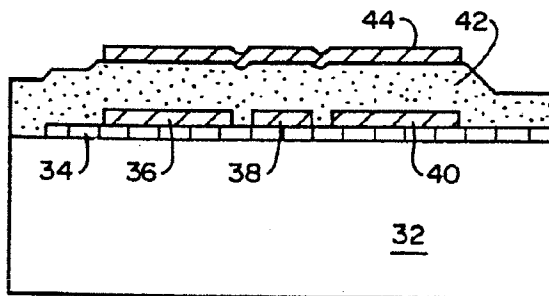
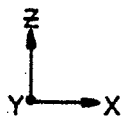


FIG. 4

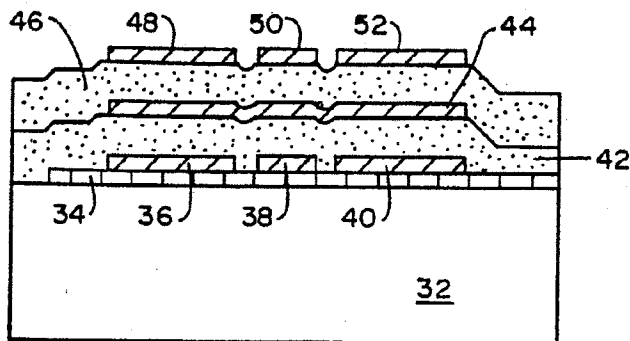



FIG. 5

KEY

 = SPACER (CLASS I) MATERIAL


 = CONDUCTIVE ELECTRODE


 = SUBSTRATE


 = PIEZOELECTRIC MATERIAL

 = COPPER (CLASS II)

 = TIP MATERIAL (CLASS IV)

 = PYREX

 = SiO<sub>2</sub>

 = NITRIDE



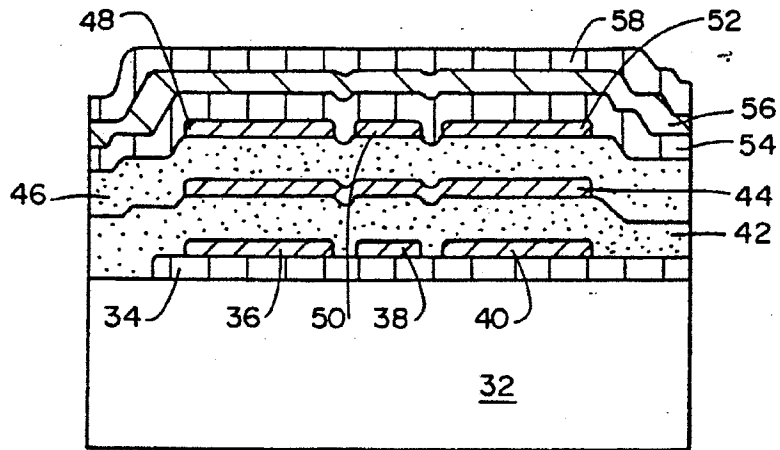


FIG. 6

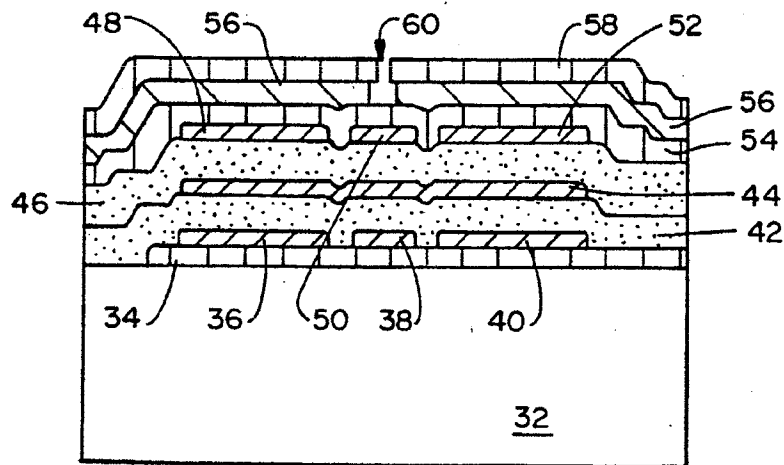


FIG. 7

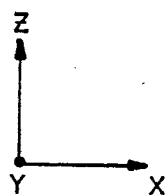
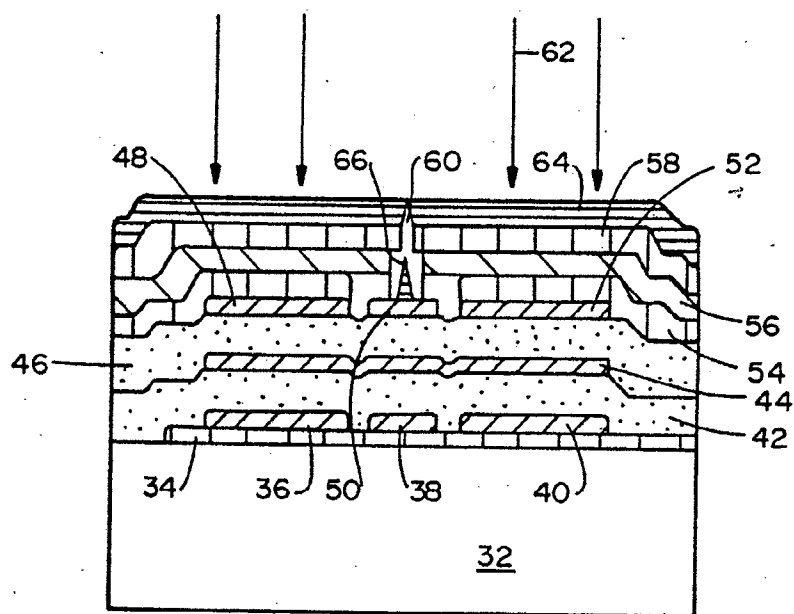


FIG. 8

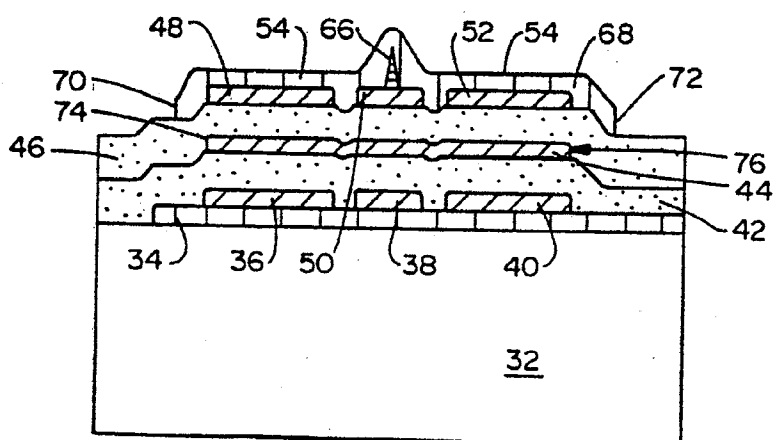
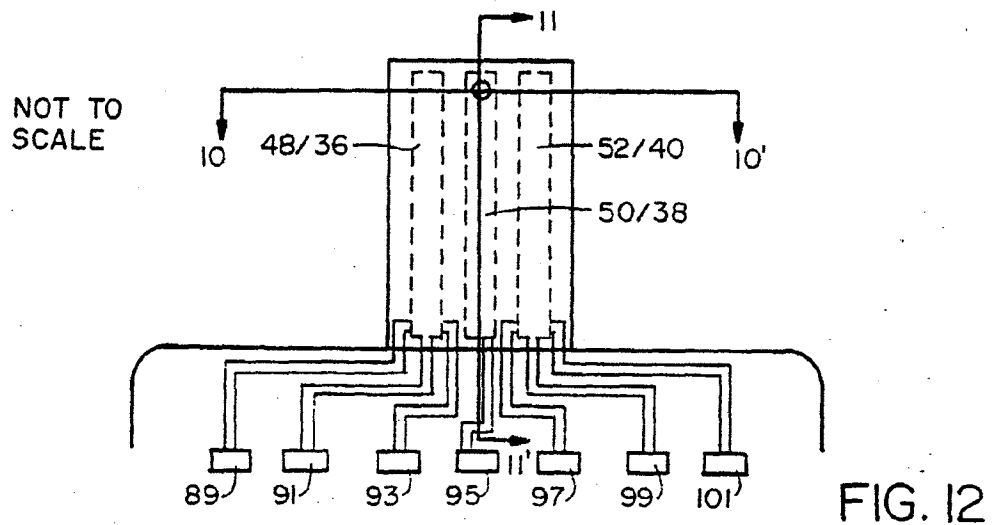
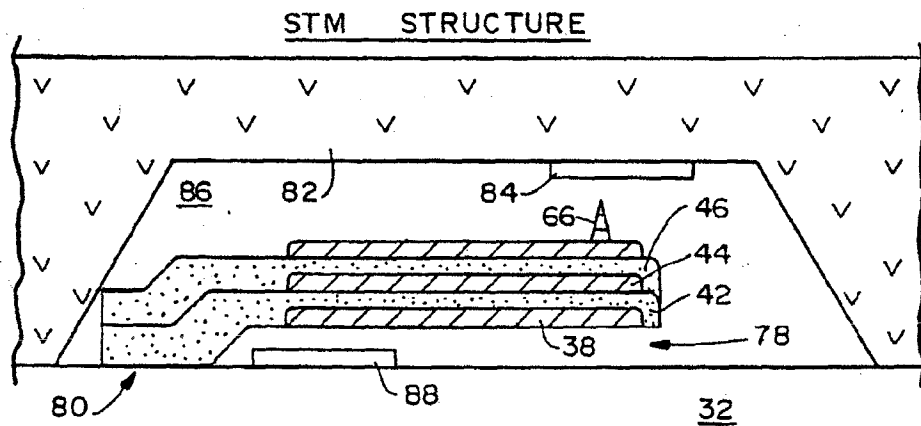
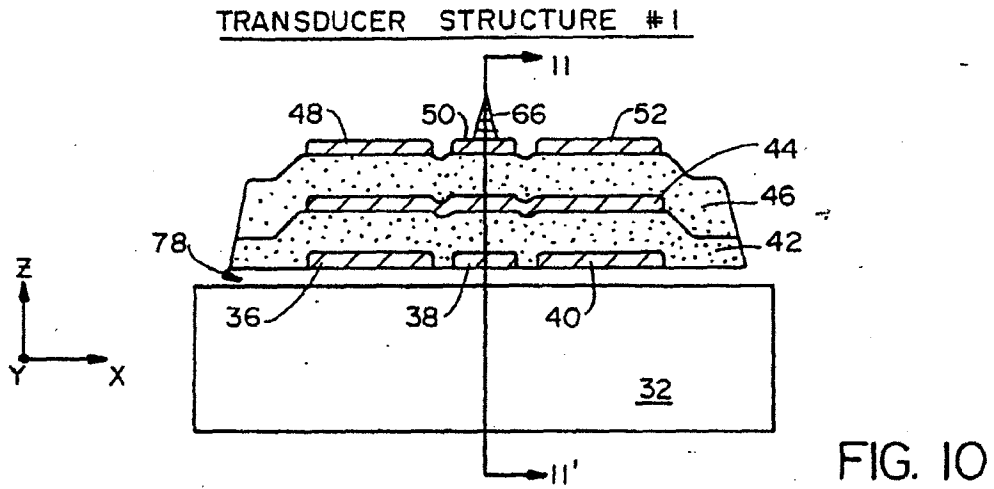


FIG. 9



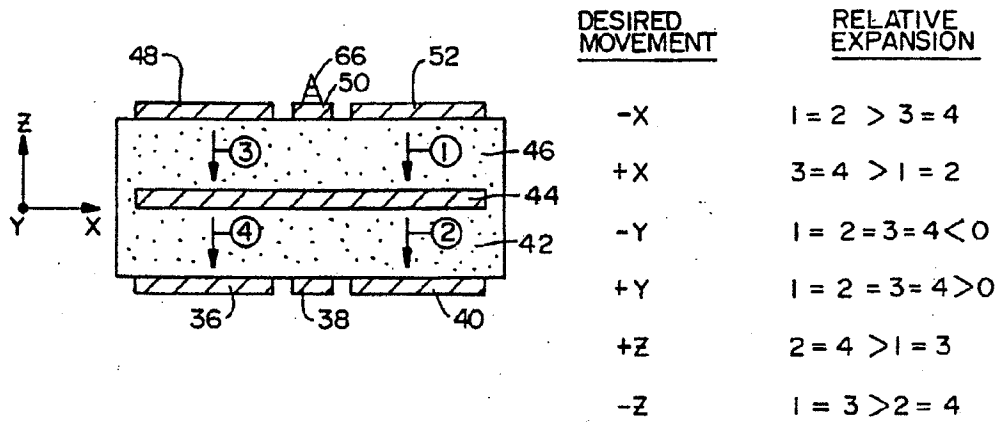


FIG. 13

FIG. 14

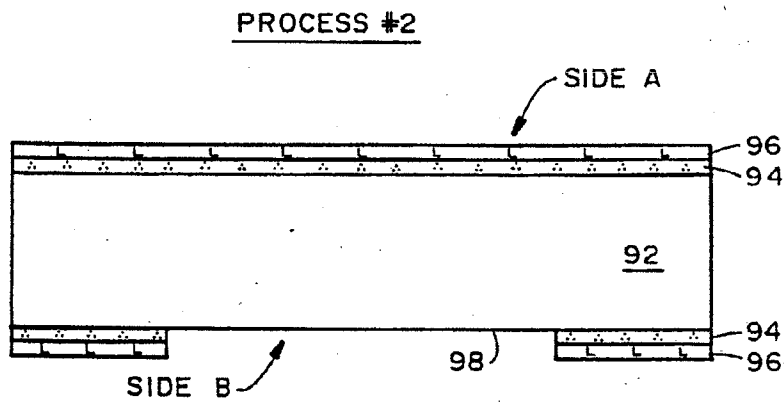


FIG. 15

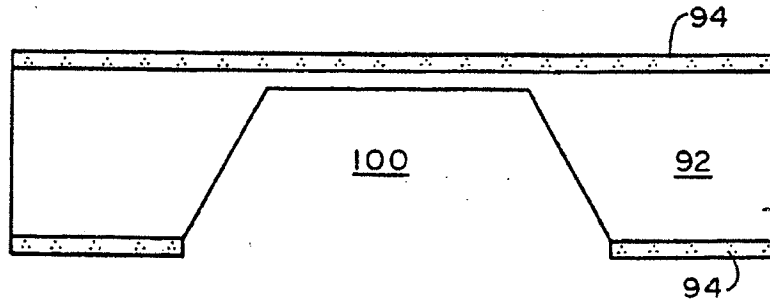


FIG. 16

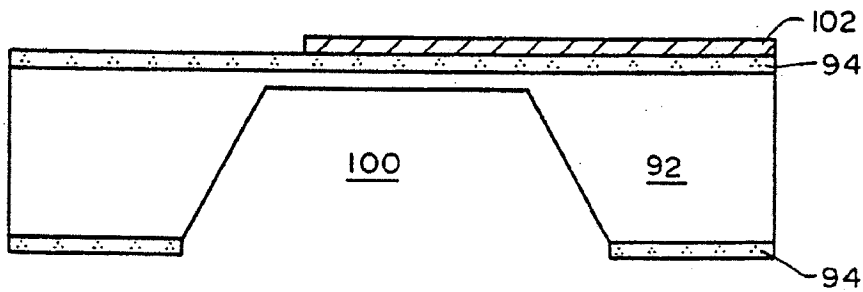


FIG. 17

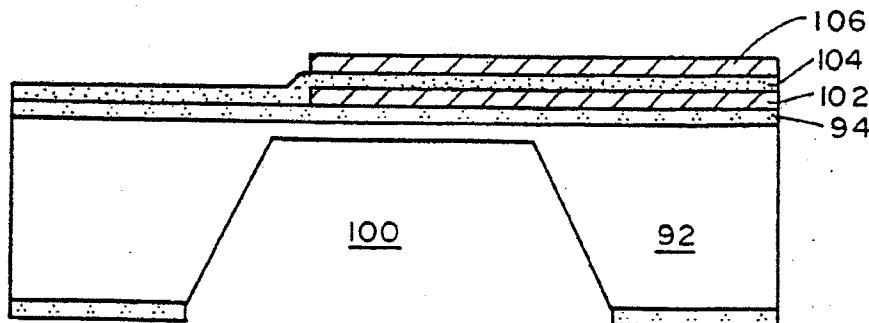


FIG. 18

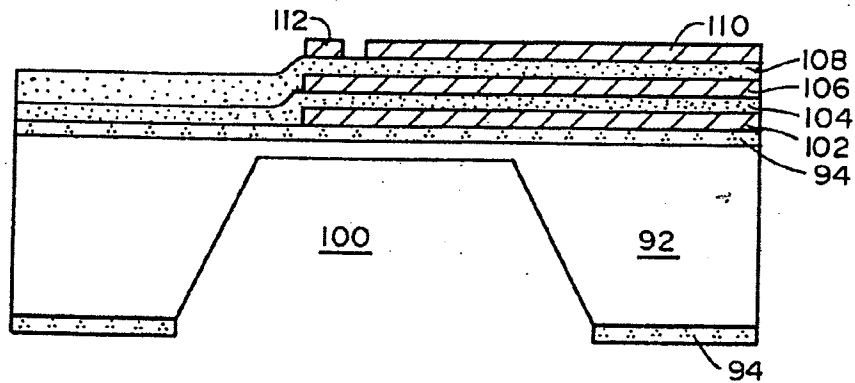


FIG. 19

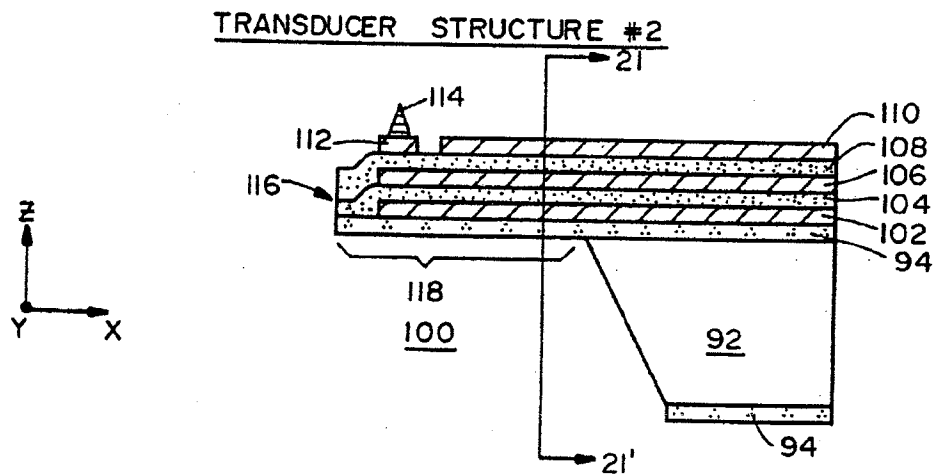


FIG. 20

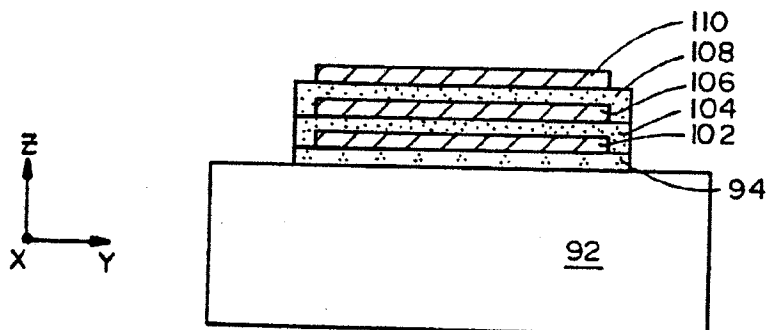


FIG. 21

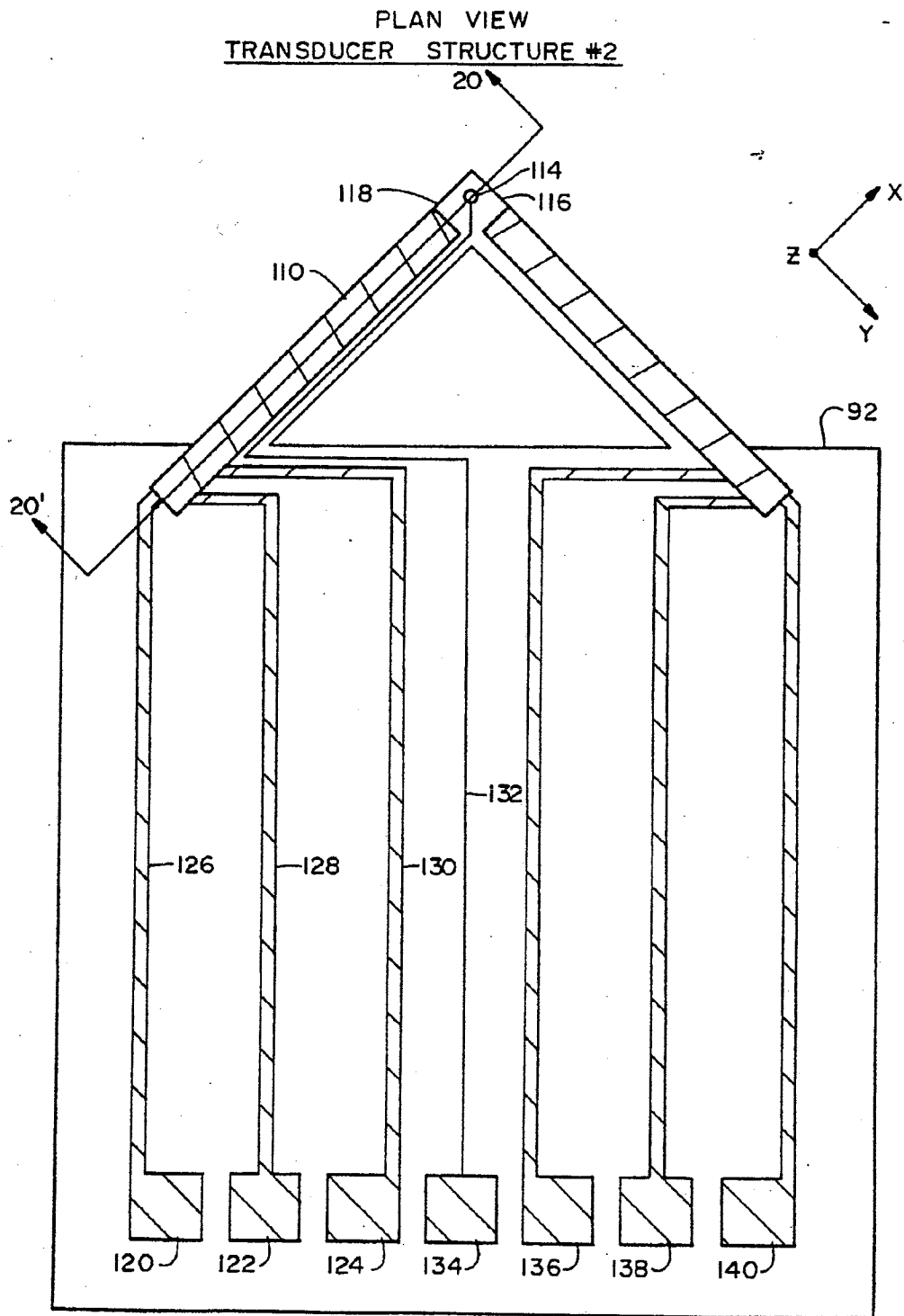
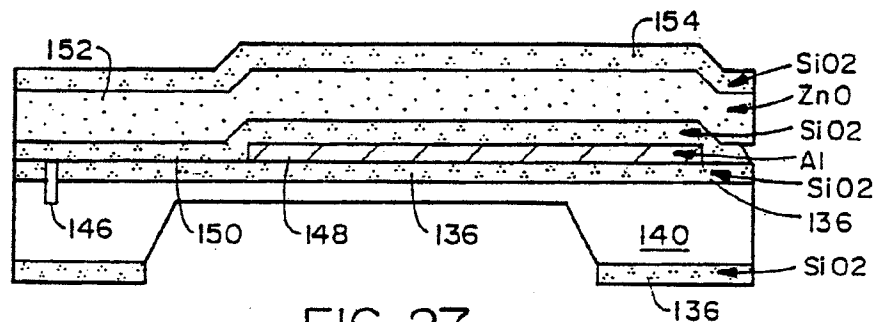
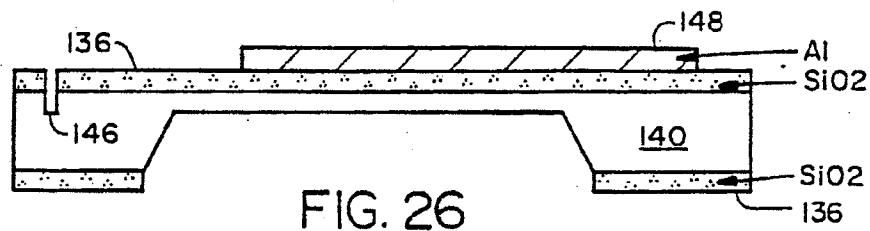
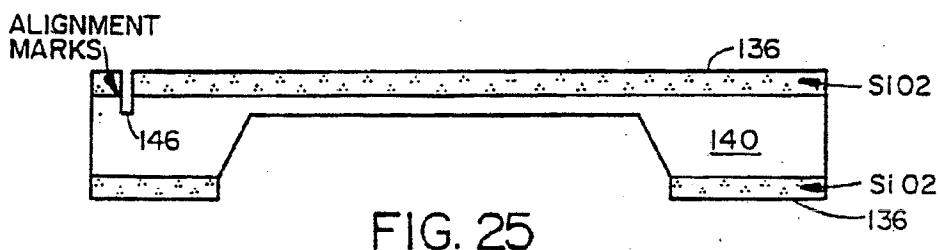
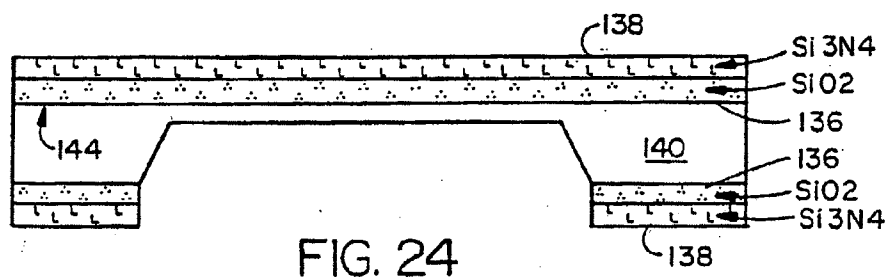
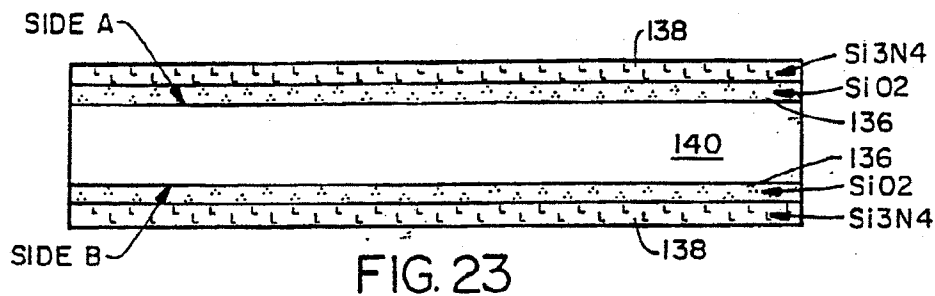


FIG. 22

PREFERRED PLANAR TRANSDUCER PROCESS





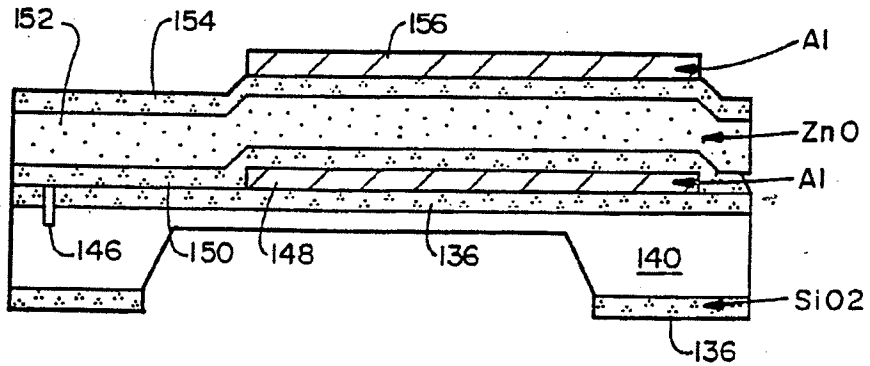


FIG. 28

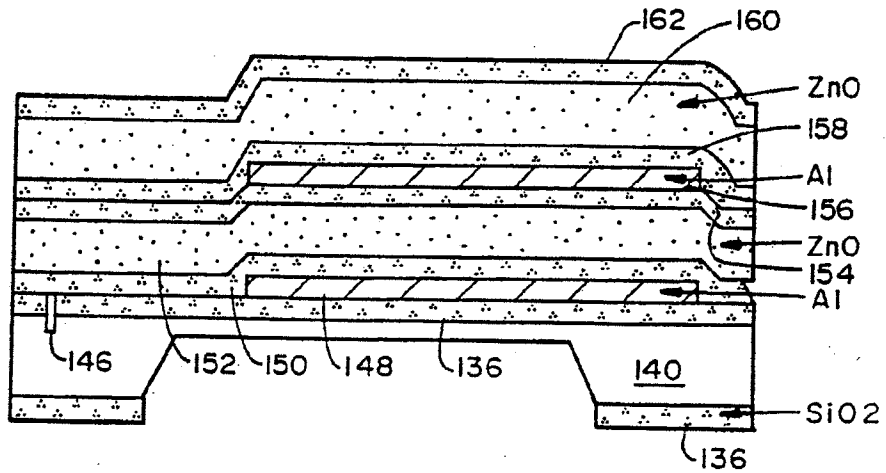


FIG. 29

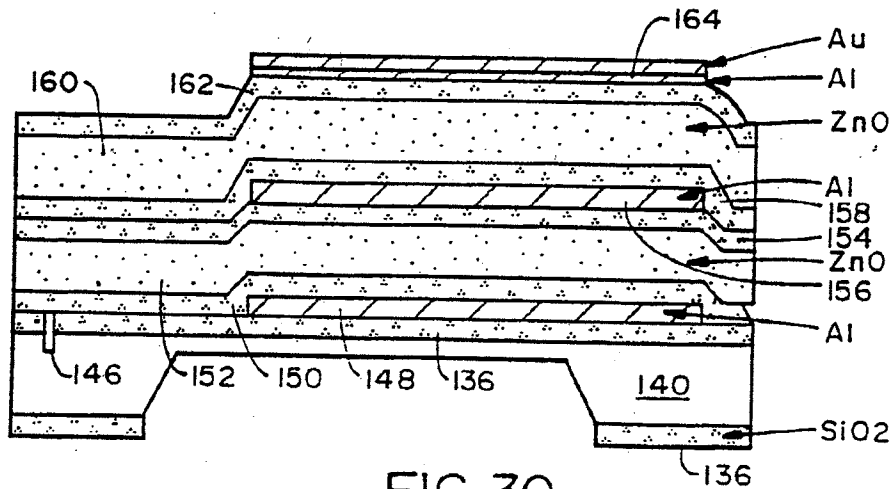
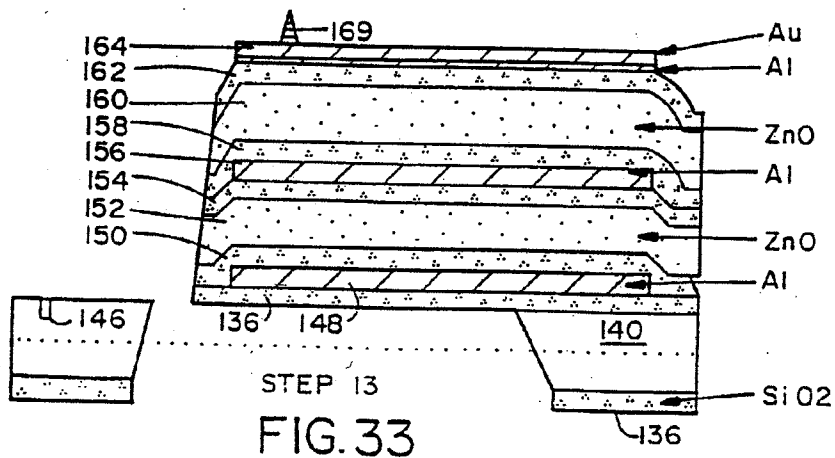
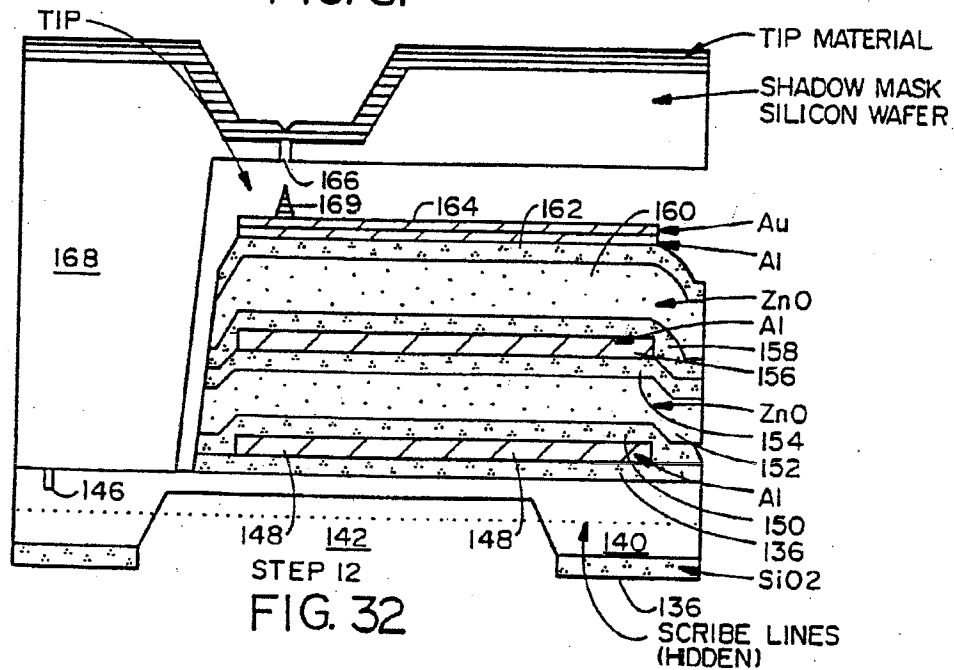
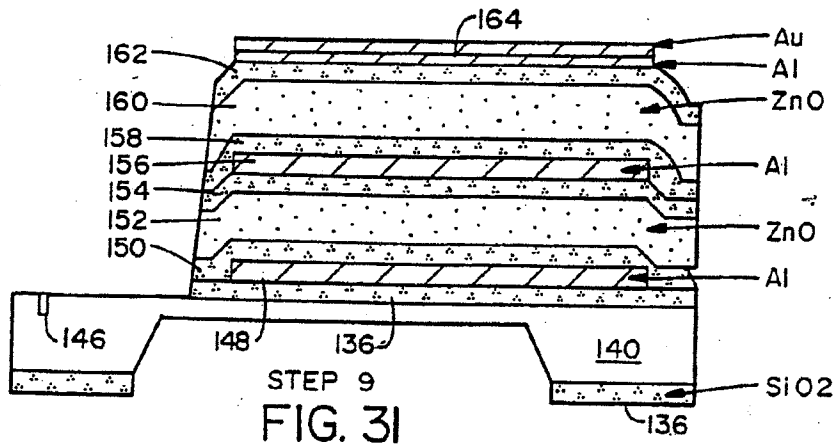


FIG. 30



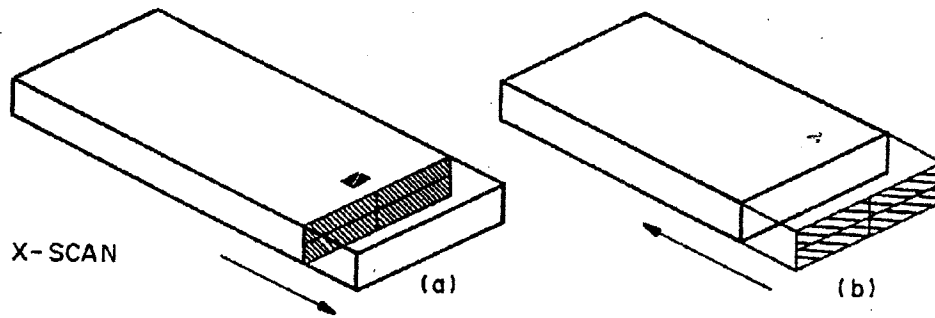


FIG. 34

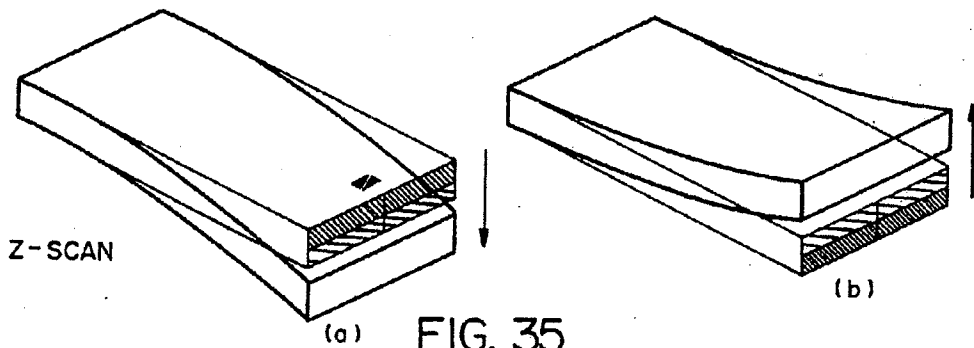


FIG. 35

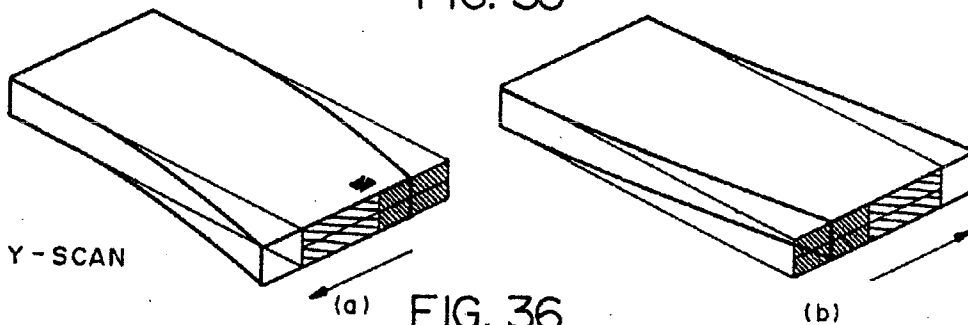


FIG. 36

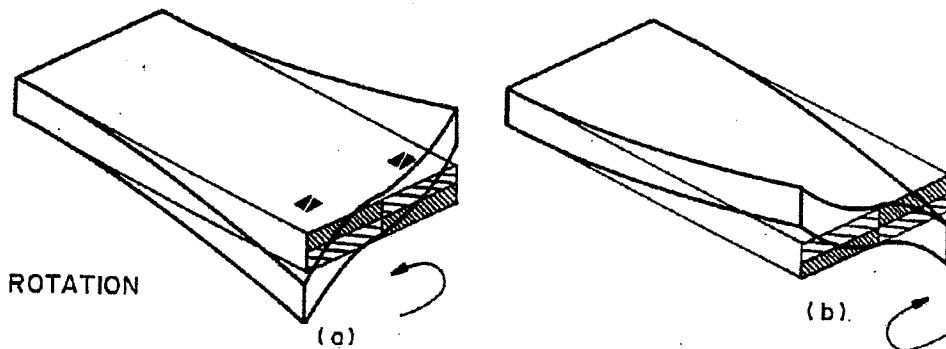


FIG. 37